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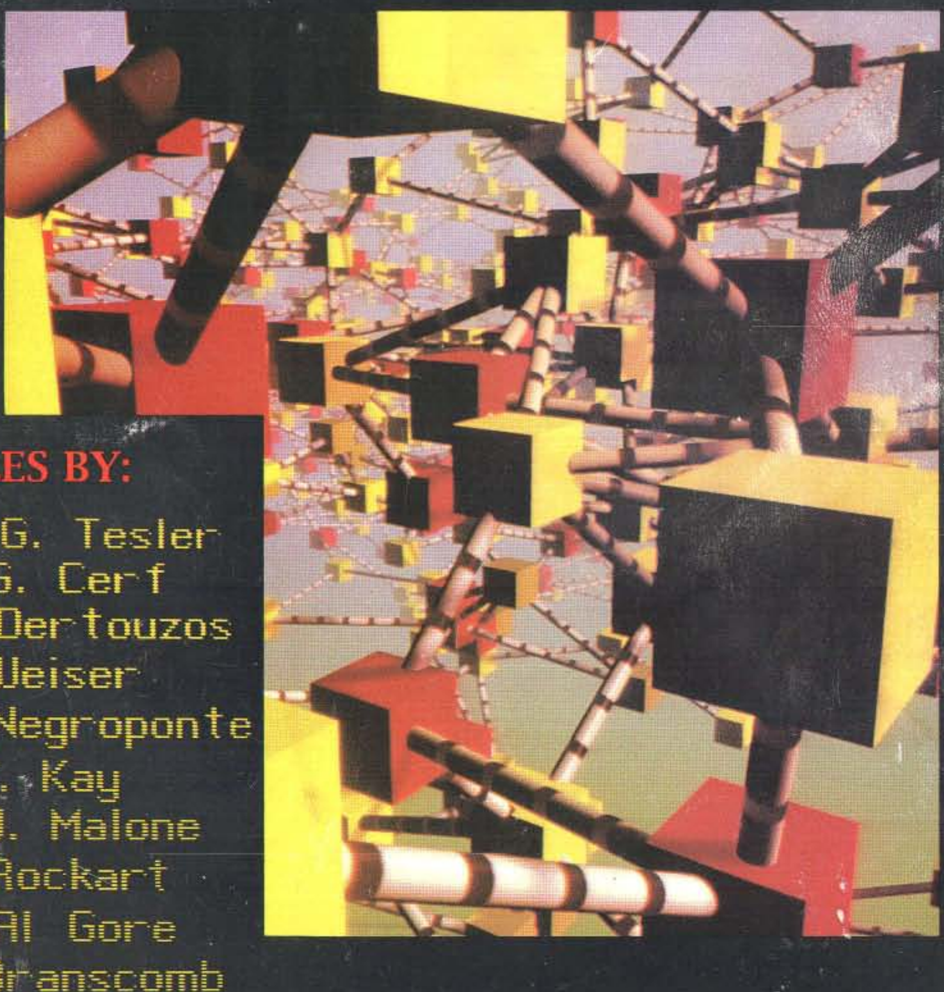
SPECIAL ISSUE

Communications, Computers and Networks



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How to Work, Play and Thrive in Cyberspace

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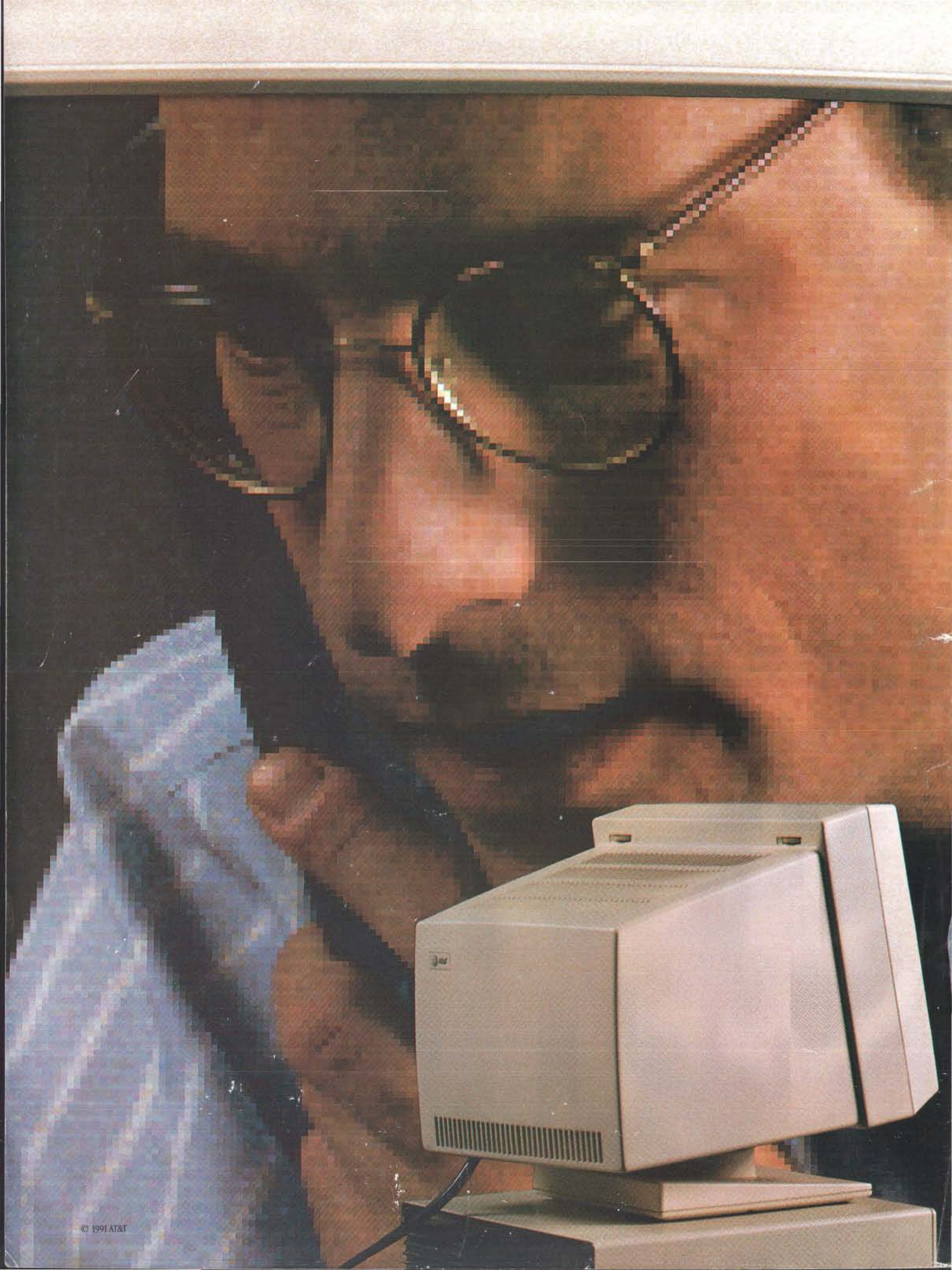

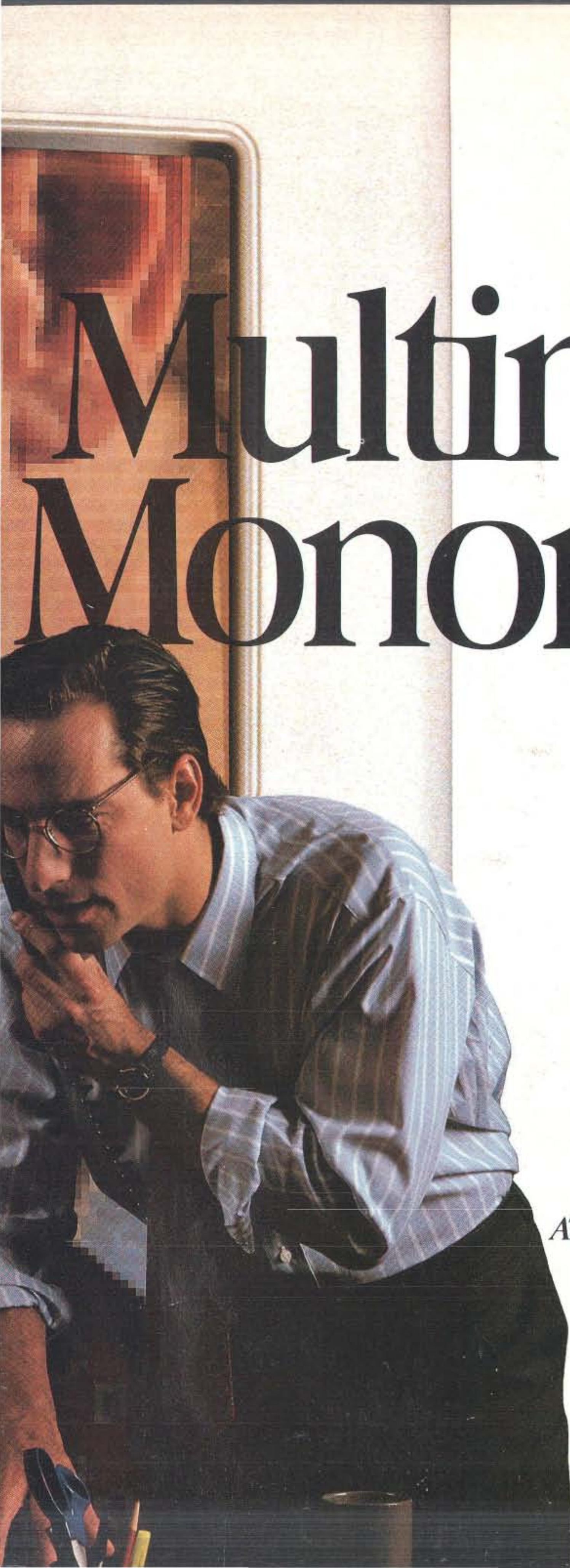

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September 1991 Volume 265 Number 3

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SPARCserver™ 470	$77,800	3.8	19.4
DECsystem™ 5500	$74,700	4	21.5

MFLOPS are LINPACK double-precision where n–100. AIX XL FORTRAN Version 2.1 and AIX XL C Version 1.1 compilers were used for these tests. SPECmark is a geometric mean of the ten SPECmark tests. All prices current at publication.

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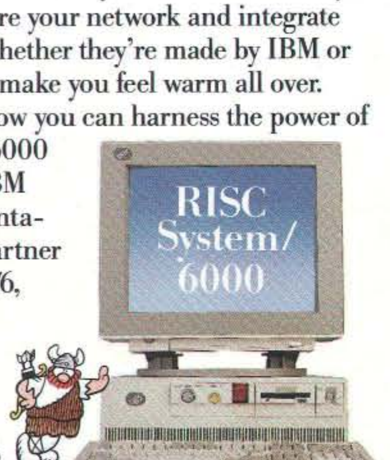

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THE COVER representation of a computer network was produced by Karl Sims of Thinking Machines, Corp., on one of the company's massively parallel computers.

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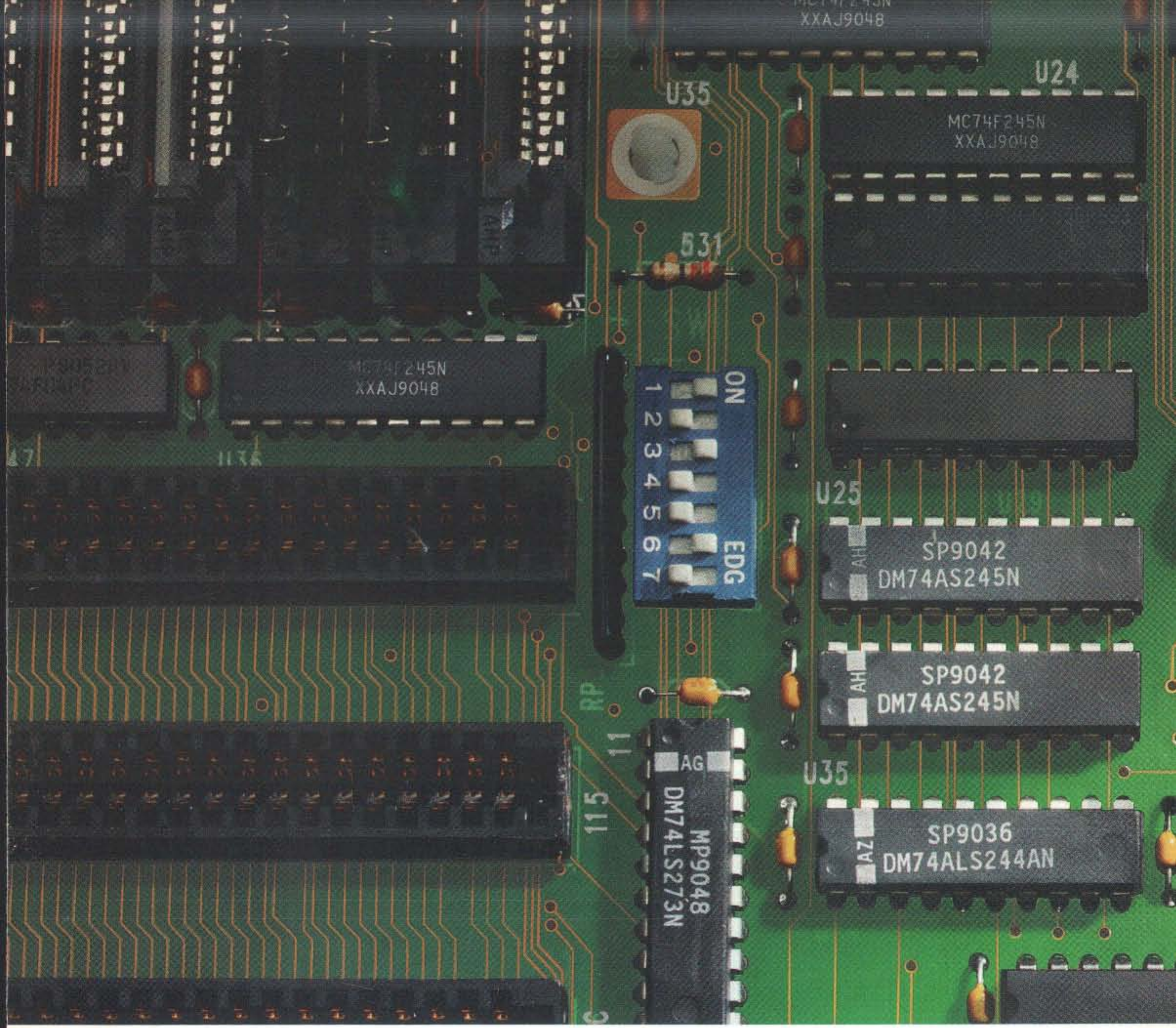

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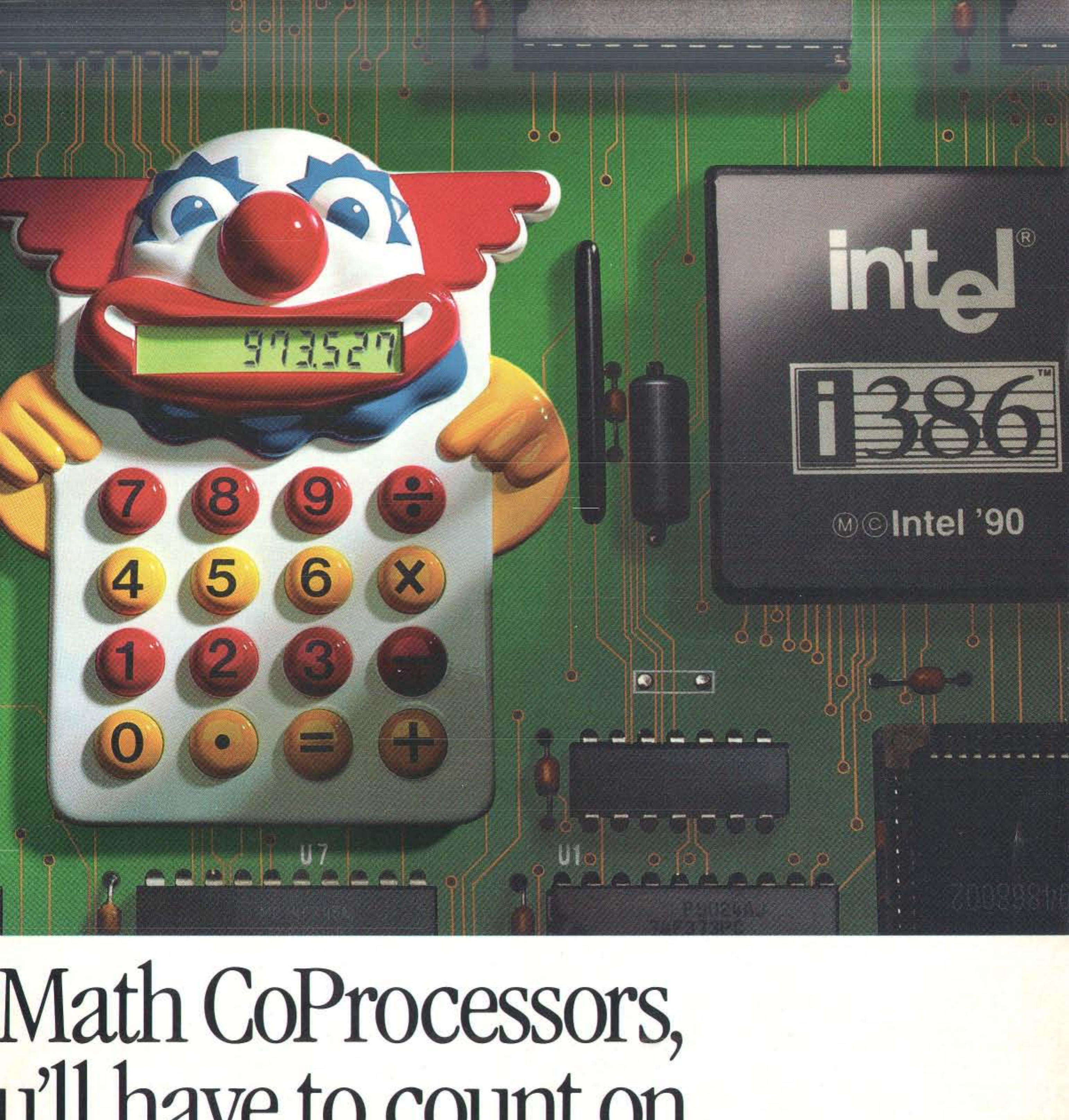

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LETTERS TO THE EDITORS

Energy Costs

In "The Real Cost of Energy" [SCIENTIFIC AMERICAN, April], Harold M. Hubbard raises several pertinent points about the externalities associated with energy production and use, but he seems surprisingly out of touch with recent economic thinking and U.S. environmental and energy security policy.

Conventional environmental economics does deal with externalities. So, too, does current government policy, through extensive efforts to lower emissions and improve environmental quality. U.S. expenditures on pollution abatement are estimated at $115 billion in 1990 alone. The Environmental Protection Agency estimates that by the year 2000 the total will climb to between $171 and $185 billion.

Political considerations of fairness and equity play a significant role in managing the environment. Many people would consider it unfair for a system to subject some areas to looser standards and greater pollution than others. Yet that result is what a simple fee system would produce. Adjusting a fee system to account for fairness makes it complex.

If we were to superimpose Hubbard's proposed system of taxes or fees on an existing system for attaining environmental or energy-use goals through command and control, we could very well end up worse off, and we would have a system far more complex than either by itself. Thus, a reasoned argument would identify not only new mechanisms for controlling externalities but also older mechanisms to scrap.

As O'Keefe points out, it is difficult to develop a fair, equitable system because environmental and social costs are a function of site location and regional characteristics. The calculation of external costs along with the evaluation of risk is an area that requires much more research.

WILLIAM F. O'KEEFE
American Petroleum Institute
Washington, D.C.

Hubbard replies:

Mr. O'Keefe appears to have missed my point. By definition externalities are costs to society that are not reflected in the market price. The incorporation of external costs into the market price of energy would reduce its real cost. One expects that the market would allocate resources more efficiently than governmentally dictated command-and-control schemes. O'Keefe's preference for such schemes seems surprisingly out of character for a representative of American business.

White House on Greenhouse

John Sununu may be right, and the vast majority of climatologists wrong ["Profile," "Science and the Citizen," SCIENTIFIC AMERICAN, April]. The greenhouse effect may indeed be nothing more than an overplayed, unsupported will-o'-the-wisp. Yet isn't it interesting that individuals like Sununu who are so cautious in financial matters are content to apply a laissez-faire philosophy to the earth's ecosystem?

After all, if the practices that emit carbon dioxide into the atmosphere are wound down, the worst that could happen would be a depression. But consider the consequences if the greenhouse theory is correct.

WILLIAM A. SMEE
Cheshire, Ore.

Anyons

Many people contributed to the discoveries described by Frank Wilczek in "Anyons" [SCIENTIFIC AMERICAN, May]. Although the idea of deriving quantum statistics from geometry and topology goes back to David Finkelstein and Julio Rubinstein in 1968 and to Michael Laidlaw and Cécile Morette-DeWitt in 1971, the first clear proposal for intermediate statistics came in 1977 from Jon M. Leinaas and Jan Myrheim of the University of Oslo. Among their other important results, Leinaas and Myrheim derived the complex phase that interpolates bosons and fermions by making a geometric argument about identical particles in two dimensions.

In 1980 and 1981, in collaboration with Ralph Menikoff of Los Alamos National Laboratory, we independently discovered these statistics in our systematic study of a novel formulation of quantum theory. Our results included many of the fundamental physical properties of anyons. Soon after, we identified their relation to the theory of braids—a generalization of the idea of exchange symmetry. In 1982 Wilczek also arrived independently at anyon statistics and carried them further, pursuing an investigation into the fractionalization of quantum numbers. Other physicists subsequently discovered applications of anyons to condensed matter physics.

The discovery of the possibility of anyons by several theoretical physicists working from different perspectives exemplifies a phenomenon that has occurred remarkably often in science: the new idea whose time has come.

GERALD A. GOLDIN
Departments of Mathematics
and Physics
Rutgers University

DAVID H. SHARP
Theoretical Division
Los Alamos National Laboratory

Finding Fraud

In "Second Guessing" ["Science and the Citizen," SCIENTIFIC AMERICAN, June], Tim Beardsley writes, "Moreover, despite the recent spate of publicized cases, ill-founded charges are more likely than out-and-out fraud." He then states that the Office of Scientific Integrity (OSI) found that misconduct occurred in only 16 out of the 110 cases it has investigated since 1989.

But we have only the word of the OSI that the charges were ill founded. The OSI keeps secret all reports of fraud investigations in which fault was not found. Remember that the predecessor of the OSI once concluded that no fraud had occurred in the David Baltimore affair. Had congressional interest not forced a more thorough investigation, innocence would have been the final verdict. There is no reason to believe that the OSI's exonerations would not similarly collapse if reexamined.

CHARLES W. MCCUTCHEN
Bethesda, Md.

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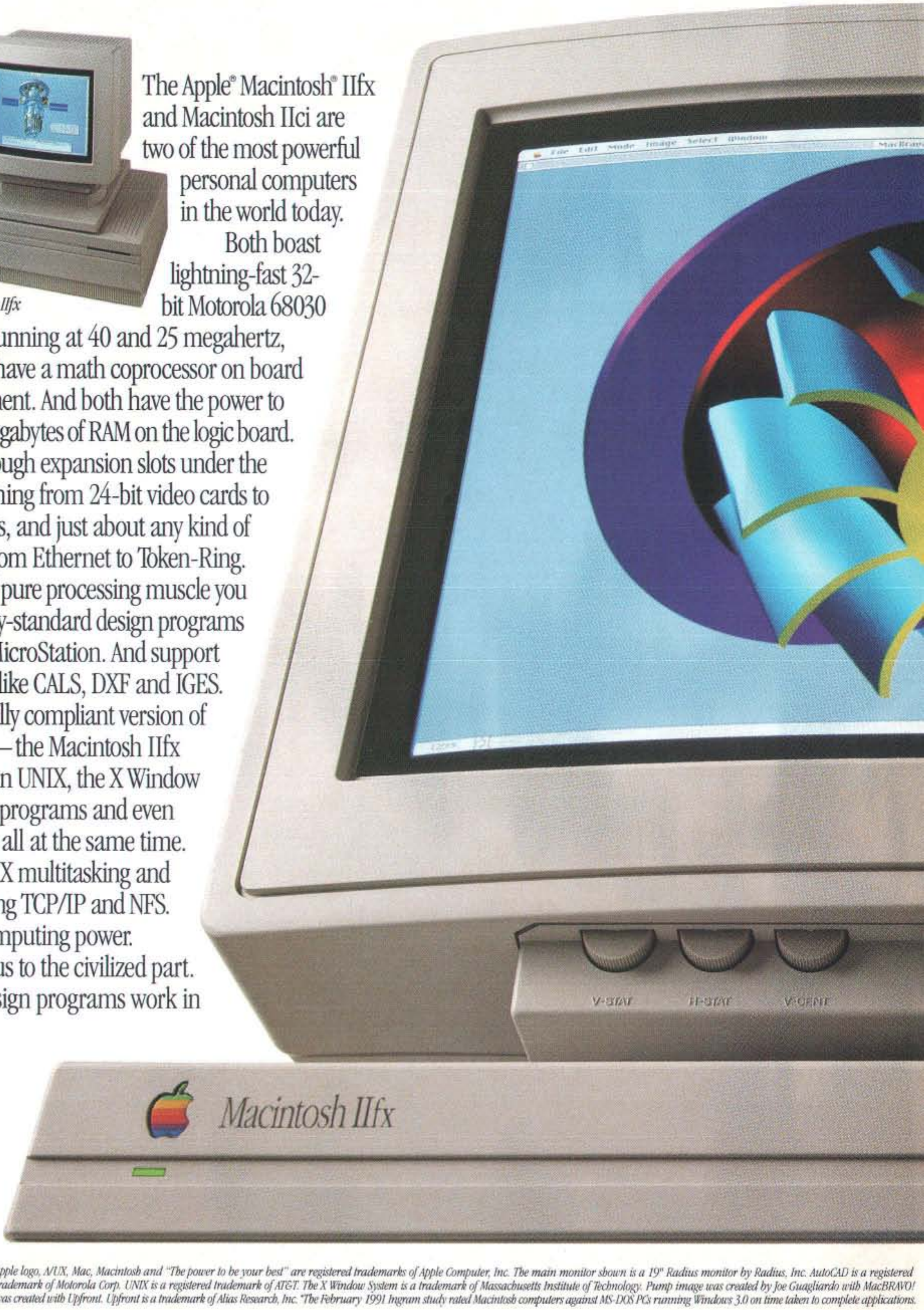
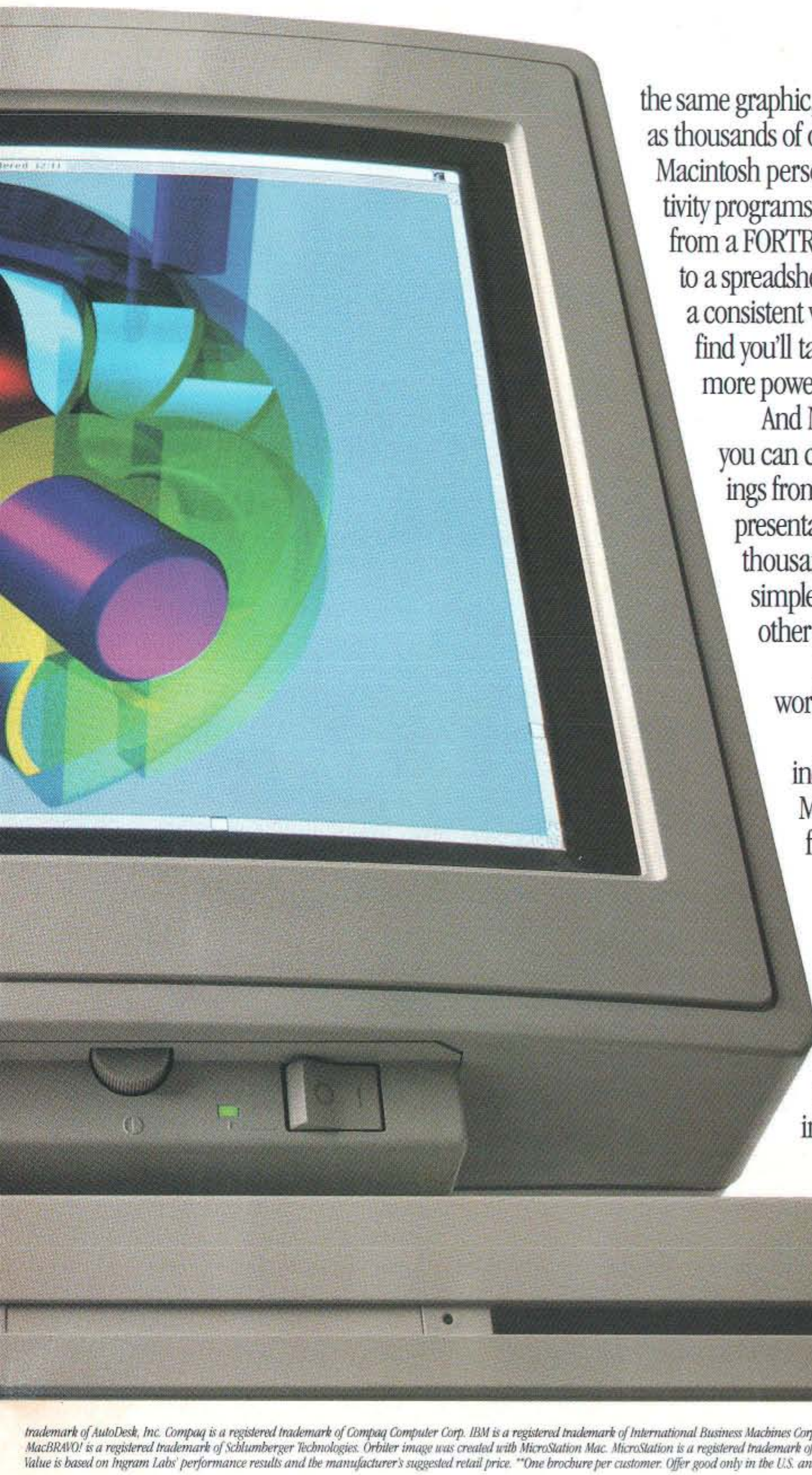


ost civilized form.



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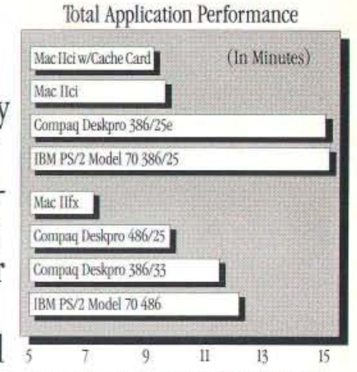

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50 AND 100 YEARS AGO

SEPTEMBER 1941

"The Associated Press carried a very interesting dispatch as far back as February 11—when there were but a few late-type American pursuit airplanes in England and fewer still in front-line action—quoting two crack RAF pilots on the behavior of the Tomahawk, one of our new pursuit jobs. 'That's a dashed fine machine. I had my legs on the Hurricane and I could even turn inside him,' declared the victor of a ten-minute mock combat. The vanquished was quoted as replying: 'You turned inside me—never thought I'd see a plane that could do that to a Hurricane. The Tomahawks are faster than I expected.' The men of the RAF are doing the fighting; they know more about air war than we do over here. When they hang rave tags on our warplanes, that praise emanates from the highest authority."

"Vaccination against epileptic fits, so to speak, to protect both public and patient against sudden seizures in traffic, at work, and under other dangerous conditions, is about ready for practical use. The epileptics are literally shocked through the brain, electrically, deliberately, into seizures. This electric shock treatment is identical with that used in treating schizophrenia."

"An archeological discovery which promises to be of the utmost significance—footprints in rock of persons fleeing from a volcanic eruption 2000 to 5000 years ago—has been made by an archeologist of the Carnegie Institution of Washington on the outskirts of the city of Managua in Nicaragua. The prints constitute the earliest known evidence of human beings in Central America, where the most advanced of New World cultures were to arise many centuries later. The individuals were fairly small people, to judge from the size of their feet. They appear to have been going toward a nearby lake to escape an eruption."

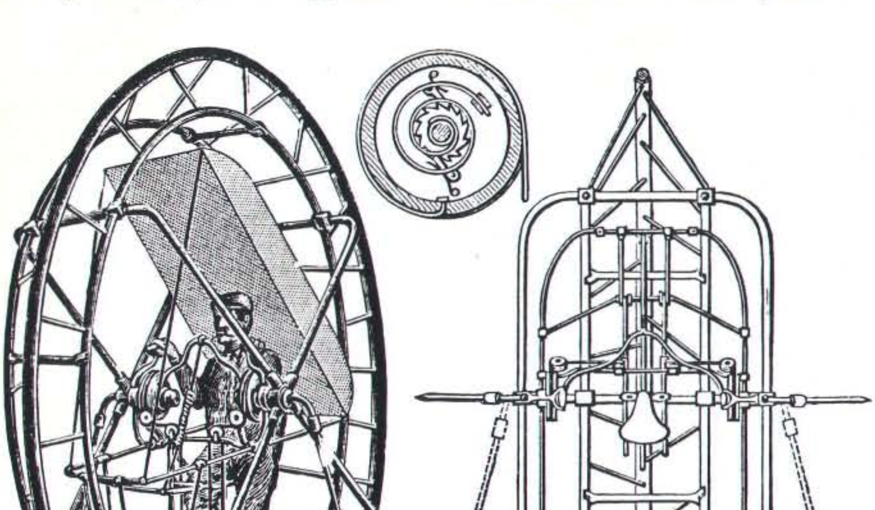
"A record of nearly 10,000 American children brought into the world with the aid of the proxy-father procedure—technically termed artificial insemination—is reported in the *Journal of the American Medical Association.* The central and Atlantic seaboard sections of the United States have the greatest number of children sired by artificial insemination. More than 97 percent of all the pregnancies resulted in living, normal babies. The number of miscarriages and abortions was only one fifth the usual rate."

SEPTEMBER 1891

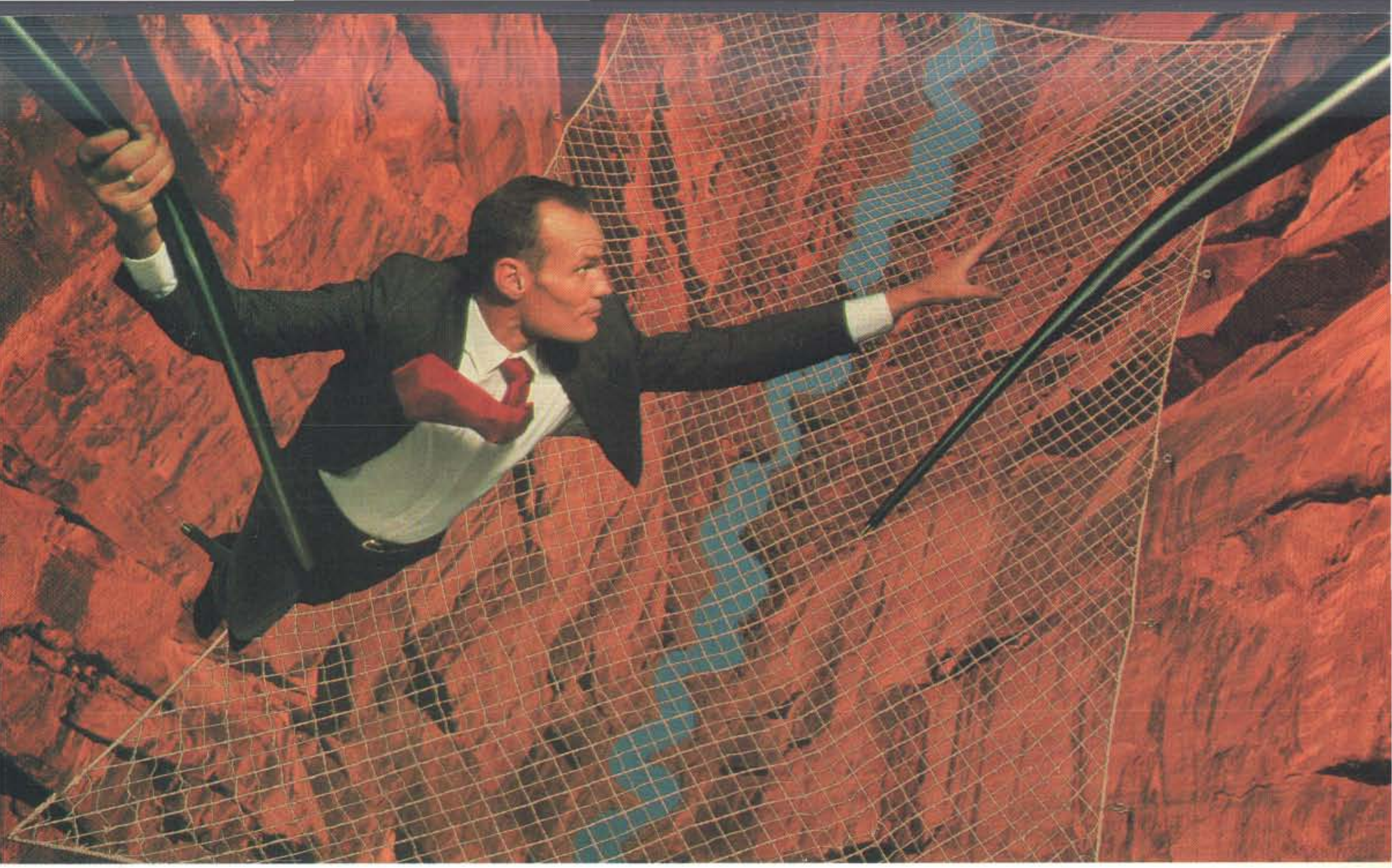
"In the case of the tunnel under the English Channel, were that carried out, it would undoubtedly afford a subterranean military road, which, were it once secured by an enemy, would be completely preserved from attack by the British navy. A tubular railway, on the contrary, would everywhere be situated above the bed of the channel, and could, therefore, be attacked at every point by dynamite. At the same time, it is so constructed and brought up along the foreshore as to be exposed for a length of no less than 3,160 feet to the direct fire of ships between the high water and low water limit."

"At the meeting of the American Association for the Advancement of Science, Mrs. Anita Newcomb McGee explained the methods and results of the Oneida Community, where between 1868 and 1879 there were sixty children born on what were alleged to be scientific principles, according to a peculiar system devised by Mr. Noyes, that separated the amative and propagative functions. It was claimed that most of these children were remarkably bright and healthy. But the spirit of monogamy prevailed, so that when, in 1879, the question was put to a vote, only three favored the continuance of the experiment."

"The machine shown in the illustration is designed to be easily and safely propelled by the rider. It has been patented by Mr. Henry C. Ross, of Ipava, Ill. A ratchet mechanism for driving the wheel is secured, by a strap, to the pedal levers. To the outer ends of the axles are attached rods long enough to extend to the ground. By raising the curved brake bar the axle is turned to throw the points of the rods down into the ground. The machine is readily steered by the handles on the arms extending from the sleeves upward at each side."



The Ross unicycle



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SCIENCE AND THE CITIZEN

Graft without Corruption

Antibody treatments could make transplanted organs acceptable

From the beginning of their surgery to the end of their lives, most transplant recipients must take drugs that weaken the immune system to prevent it from rejecting the genetically foreign tissue. Among other side effects, those drugs leave a patient susceptible to infection. Denise Faustman, an immunologist at the Massachusetts General Hospital and Harvard Medical School, is unhappy about that approach. "If you look at the transplant literature, almost everybody is working on suppressing the recipient," she sighs. "They haven't asked, 'Why don't we try something significantly less toxic by treating the organ and leaving the patient intact?'"

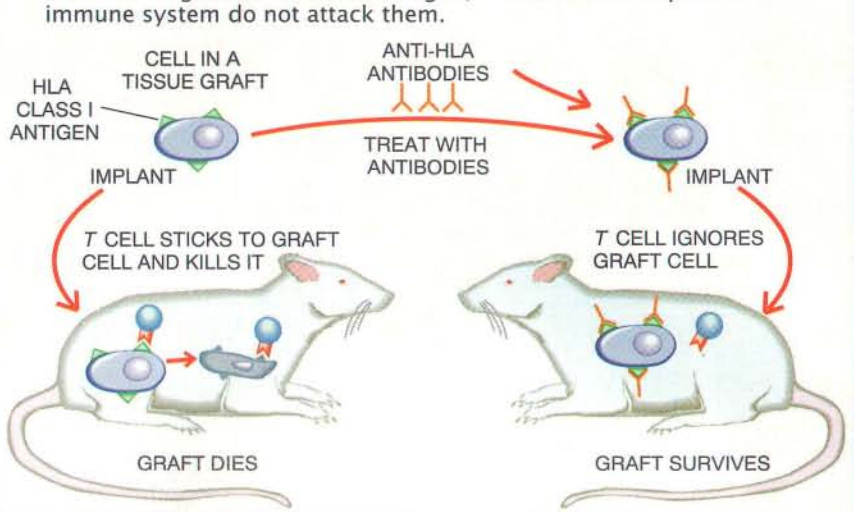
Faustman and her colleague Chuck Coe recently reported a technique that may overcome the rejection of clinical transplants without compromising the immune system when patients need its protection most. By coating cells with antibodies against a critical protein, the researchers gave grafts a "nonstick" surface that the immune system ignored.

All the more striking is the fact that the donors and the recipients of the grafts were not merely dissimilar—they were members of different species. In their experiments, Faustman and Coe implanted human cells into mice. If further research shows that treating tissues can also make animal cells acceptable to the human immune system, the investigators hope it could finally open the way to using such xenografts instead of depending entirely on donated human organs, which are scarce.

"I think the work is extremely interesting, first-rate stuff," comments Keith Reemtsma, chairman of the department of surgery at the Columbia-Presbyterian Medical Center and a pioneer in xenograft research. Past attempts to modify donor organs have been disappointing, Reemtsma says, which is why the work by the Massachusetts group is particularly intriguing. He is hopeful that the method will also prove useful in human-to-human transplants. "If it's going to work with xenografts, it's going to work in allografts," he adds.

Protecting Grafts with Antibodies

When grafts of pancreatic islet cells are protected with monoclonal antibodies against HLA class I antigen, *T* cells in the recipient's immune system do not attack them.



Organ rejection is controlled by *T* cells, which prowl the body in search of infected or abnormal cells. The *T* cells recognize faulty cells by the antigen peptides, or protein fragments, that they display. Before inspecting a cell's antigens, however, a *T* cell must first stick to the cell by binding briefly with certain adhesion molecules, called epitopes, on its surface. Faustman and Coe reasoned that by hiding these molecular "handholds" on grafted tissues, they could interfere with transplant rejection.

The investigators tested their idea with the most extreme tissue mismatch possible, a xenograft. They focused on one particularly important epitope, the human lymphocyte antigen (HLA) class I molecule. In humans, HLAs are the most important determinants of tissue compatibility between graft donors and recipients. According to Faustman, HLA class I antigens also seem to be the predominant epitopes on the insulin-making islet cells of the pancreas, liver cells, kidney cells and those of other parenchymal tissues. The researchers therefore developed monoclonal antibodies that would bind specifically to HLA class I antigens.

As Faustman and Coe described in *Science*, pretreating grafts of human tissue with the antibodies invariably promoted graft survival in mice. Whereas untreated islet cells were rejected in less than a week, treated cells functioned healthily for the 200 days of the study. Grafts of treated tumor tissue actually grew in their new hosts. Moreover, the treated grafts had the additional effect of inducing what Faustman calls "graft-specific unresponsiveness." The hosts stopped rejecting untreated grafts of the same tissues from the same donors.

Indeed, the success of the transplants was so remarkable that the reasons for it are somewhat mysterious. By obscuring the HLA epitopes, the monoclonal antibodies presumably make it difficult for *T* cells to adhere to the grafts. Inside the body, however, the antibodies must wear away or degrade over time. They also could not have protected the cells that grew from the grafts or that were transplanted later.

Faustman's results suggest that the "slipperiness" conferred by the antibody treatment persists long enough for other immunologic mechanisms to learn to accept the grafted tissue. "We know that there is this teeter-totter in the immune system"—a delicate balance of regulatory activities—"that we wish we knew more about," Faustman says.

Human clinical studies of antibody-masked grafts may still be five years off. Some types of patients, such as diabetics, may benefit from transplants of isolated cells or diffuse tissues like pancreatic islets. To be more widely useful, however, the technique must still prove its worth with whole tissues and organs, which express a wider variety of epitopes.

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A specially-equipped van serves as a lab on wheels to test a variety of new automotive sensors. The Hughes Aircraft Company-designed mobile testbed, called the Automotive Sensor Instrumentation System, incorporates various sensors, computer-controlled signal conditioning circuits, and monitoring and data-recording equipment. An extensive array of sensors is mounted on a platform attached to the front bumper of the van. A video camera and an infrared camera, also mounted on the front of the van, show what's ahead, while a radar and laser rangefinder provide range and range rate data. Hughes is using the van to study and evaluate various technologies for potential use in advanced automotive sensing systems.

A state-of-the-art on-line computer graphics projector helps to manage a network of 300 host computers at General Motors' information services subsidiary. Seven Hughes-built Superprojectors, operating around the clock in the EDS Information Management Center in Plano, Texas, give more than 100 up-to-date network status reports (operations bulletins, maps) and other network management information. The Superprojectors, connected to display-generating computers, project images with resolutions in excess of 1,000 TV lines into 14x16-foot screens. Originally used for displaying information in military command-and-control centers, the projectors use Hughes-developed liquid crystal light valve technology.

Display technology from fighter aircraft may make driving easier for wearers of bifocal eyeglasses. The technology, developed by Hughes and known as Virtual Image Display, replaces the speedometer, gauges, and warning lights in a typical car instrument panel with a projected image created by a sophisticated set of mirrors and lenses. This image appears to be behind the dashboard, approximately six feet away from the driver, eliminating the need to shift from distance vision to near vision when reading the instrument panel. Drivers with bifocals may be able to drive and read the instruments without their glasses.

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AMRAAM's first ground test launch confirms laboratory analysis and simulations of the missile's performance when fired with zero initial velocity. In the tests, a next-generation Advanced Medium-Range Air-to-Air Missile (AMRAAM) was fired from a standard F-16 aircraft missile rail launcher mounted at a 30-degree elevation from the ground. The Hughes-built AMRAAMs, combined with the TPQ-36A three-dimensional radar, are part of a joint program with Norsk Forsvarsteknologi of Norway to help the Royal Norwegian Air Force create a totally new Advanced Surface-to-Air Missile capability.

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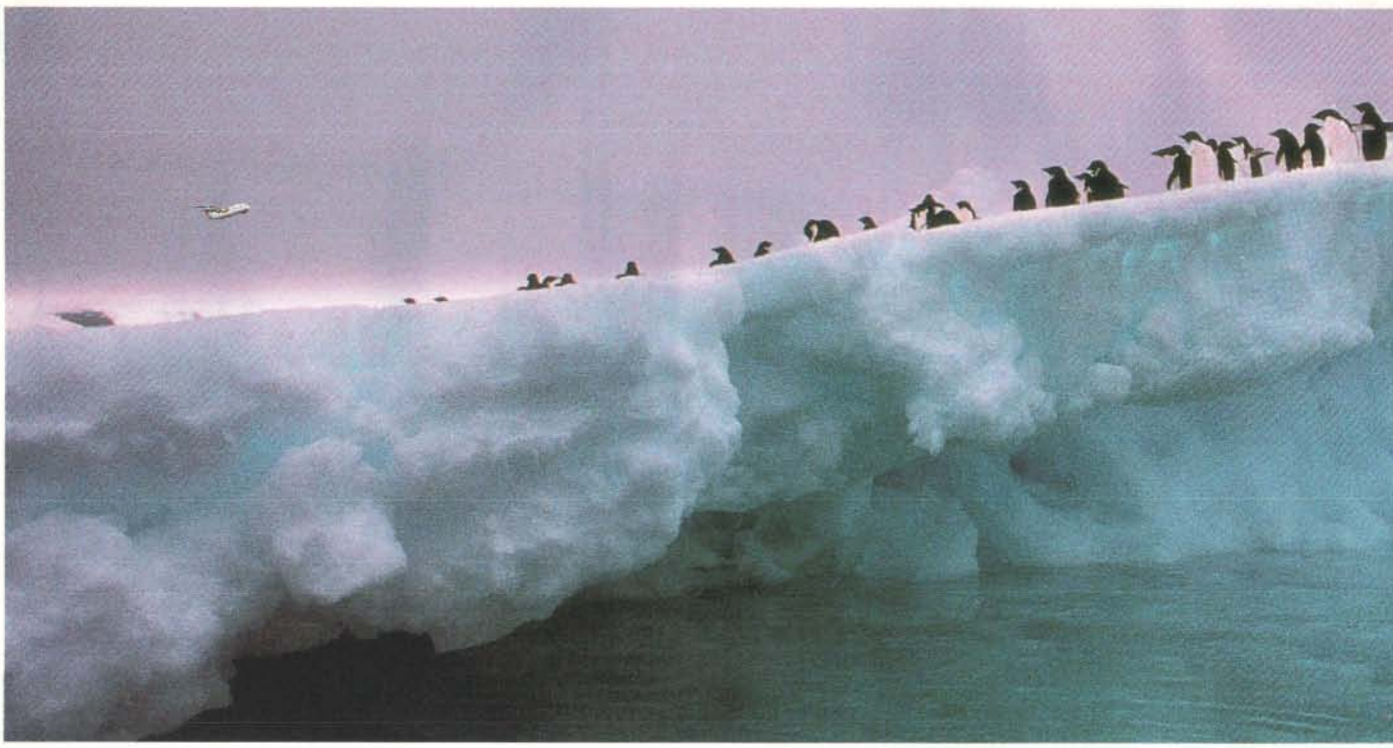

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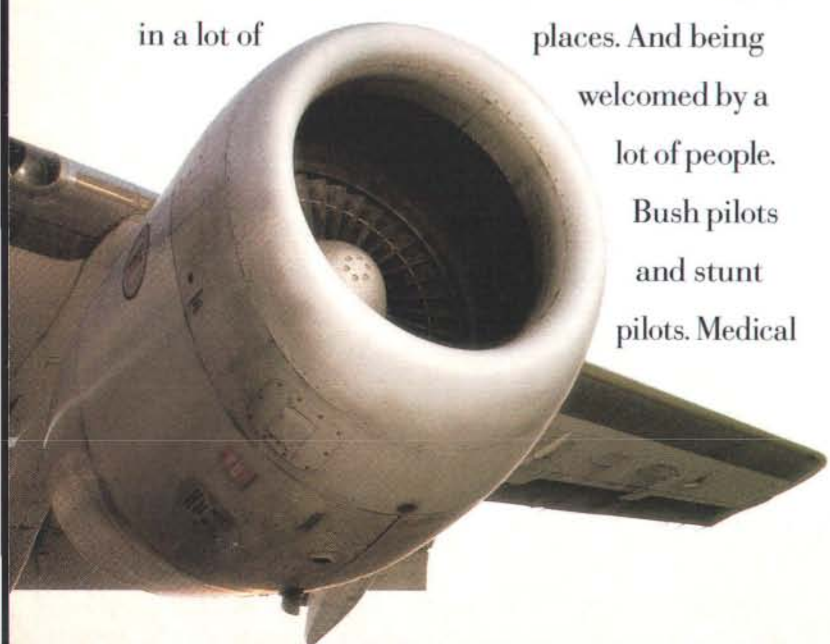

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Faustman says her group is now working on a polyclonal serum of antibodies against many essential epitopes. The idea is to "just mask 'em all prior to transplantation," she says. But she also acknowledges that "realistically, for a solid tissue, you're probably going to have to use it with another form of treatment. So maybe you could do brief immunosuppression for a couple of months and then wean people off it."

The unsuccessful case of Baby Fae, an infant who died after receiving a baboon's heart to repair a birth defect in 1984, tainted the image of xenografts. But Faustman and others remain convinced that xenografts are the only hope of making enough donor tissues available to all the people who need them. "There are only about 4,500 organ donors in the U.S. every year," she argues. "The supply-and-demand problem is going to be impossible." Organs from animals that have been modified to reduce human rejection may be important for meeting the demand. —*John Rennie*

Elusive Quarry

Researchers are closing in on the stem cell

Somehow the bone marrow spawns all the specialized blood cells the body needs—lymphocytes, granulocytes, red blood cells and platelets, to name but a few. Investigators have concluded that this feat is accomplished by stem cells, which can replenish themselves indefinitely and differentiate on demand. But these cells have never been isolated in humans. Although one in every few thousand bone marrow cells is thought to be a stem cell, they look just like many other types.

Now two research groups, using two different approaches, seem to be homing in on the evasive target. A team headed by Malcolm A. S. Moore of Memorial Sloan-Kettering Cancer Center is vying with California researchers Charles M. Baum of Systemix, Inc., in Palo Alto and Irving L. Weissman of Stanford University. In recent months, both teams have improved the techniques for concentrating the number of stem cells in cultures and demonstrating their activity.

The ability to obtain a pure supply of stem cells from bone marrow or blood would provide physicians with an important lifesaving tool. They would be able to regrow the entire blood-producing system in patients whose bone marrow tissues had been damaged by disease or by chemotherapy. Stem cells would also be valuable as targets for gene therapy of inherited or even infectious diseases. Because they renew themselves, genes introduced into the cells would persist for the whole of a patient's lifetime.

At present, the marrow of leukemia or other cancer patients who cannot find a suitable donor (usually a close relative) can be reconstituted from a small number of cells. But techniques for eliminating diseased cells from the marrow are far from perfect. The risky procedure consists of taking a sample of bone marrow cells, then killing all the cells left behind in the patient's marrow by drugs or irradiation. Later the sample is returned to the marrow to reseed the blood-producing system. "The closer you can get to the stem cell, the less likely it is there will be contamination," Moore says.

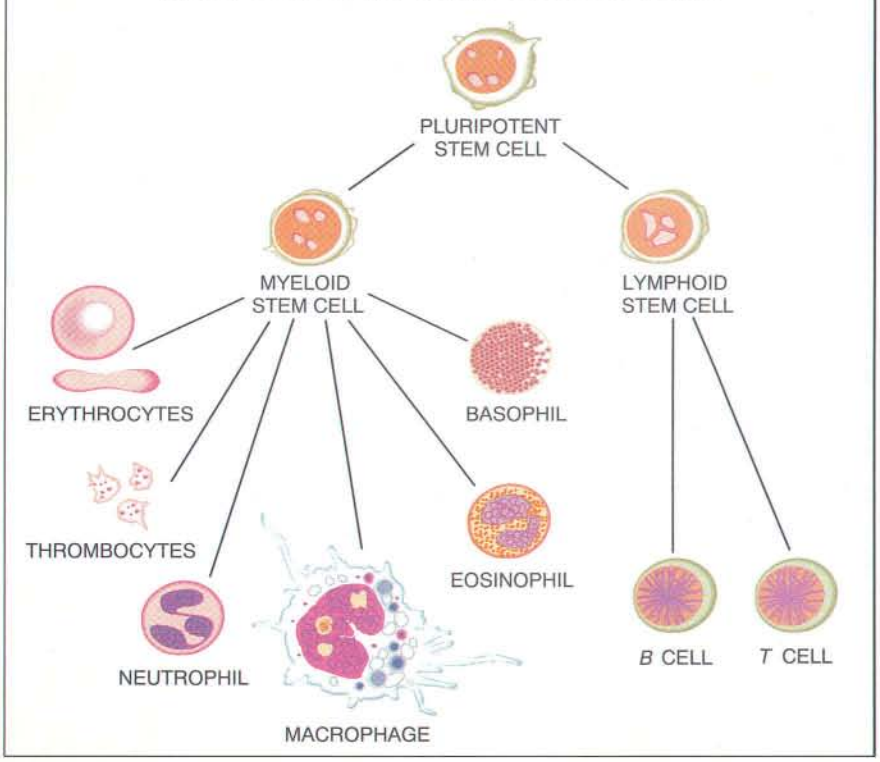
Moore and his colleagues are getting closer to the stem cell with a series of screens that use artificial antibodies to recognize and exclude differentiated cells. The quiescent stem cells are among the tiny fraction of cells that survive. The researchers then induce these cells to multiply, using a special tissue culture designed to mimic conditions in the bone marrow.

Stem cells and their immediate descendants are very finicky about what kind of environment they need to grow in. In particular, they must be supplied with cytokines, protein growth factors secreted by other cells in the blood. Moore has recently shown that a protein called the *kit* ligand, in combination with other growth factors, is quite effective in stimulating stem cells to grow rapidly. *Kit* ligand was originally identified as the product of a gene that can disrupt blood formation in mice, and many researchers are now studying it. Moore believes human stem cells have a *kit* receptor that needs to bind to ligand to achieve maximal growth.

Still, it is no simple matter to prove that the cells Moore has isolated are indeed stem cells. The only way to be absolutely certain would be to introduce a single stem cell into a volunteer whose marrow has been totally destroyed. Because scientists can hardly perform that experiment, Moore's group has relied on a variety of substitute tests that examine the ability of cells to form long-lasting clones. "We have developed a quick and simple assay that detects cells with long-term proliferative ability," Moore says.

Moore is confident his procedures for isolating stem cells do preserve the cells' ability to generate all the components of blood. But his tests do not di-

Stem Cells and Their Descendants



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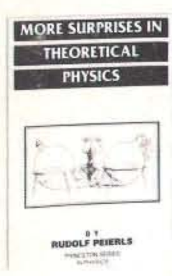

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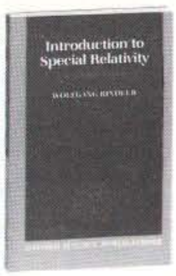

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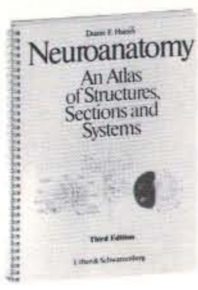

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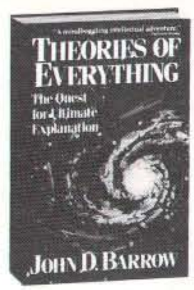

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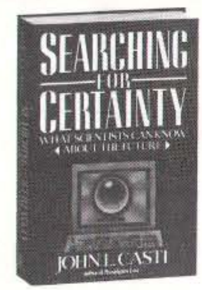

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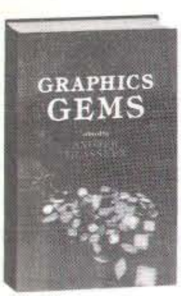

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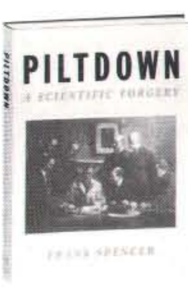

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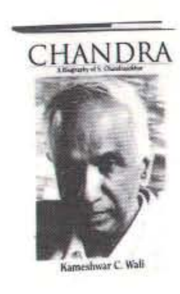

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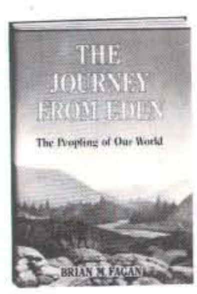

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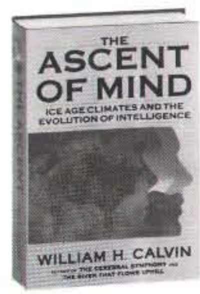

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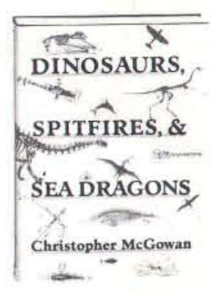

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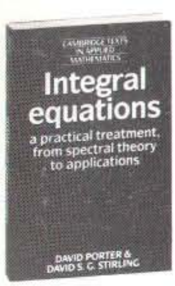

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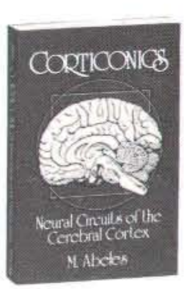

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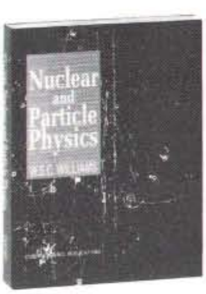

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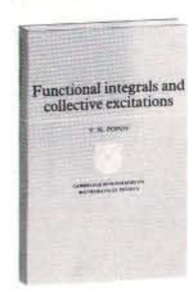

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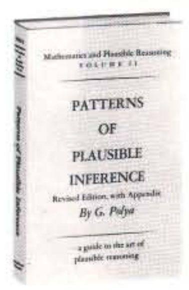

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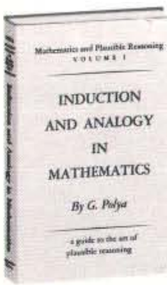

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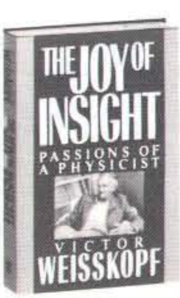

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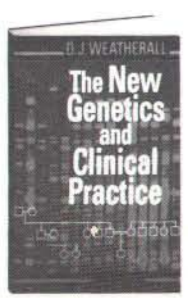

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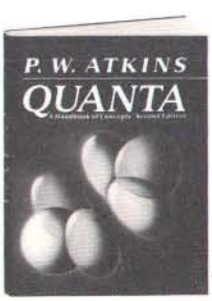

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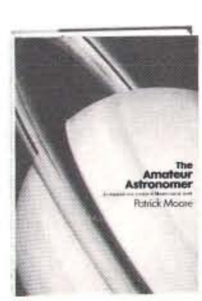

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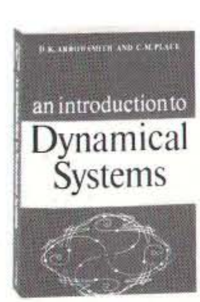

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Gravity's Rainbow

Most people who chase after mirages end up miles from water. But for astronomers, mirages are an oasis from which knowledge springs. David L. Jauncey of the Australia Telescope National Facility and his co-workers have found what may be the oddest cosmic illusion of them all: a gigantic ring that is one of the brightest sources of radio waves in the sky.

In 1936 Albert Einstein predicted that such rings could be produced when two objects at different distances from the earth happen to lie along the same line of sight. Like the heated air that forms mirages on the earth, the gravitational field of the object in the foreground acts like a lens and bends the light from the more distant object. If the two objects coincide in the sky exactly, the image of the more distant one forms a ring.

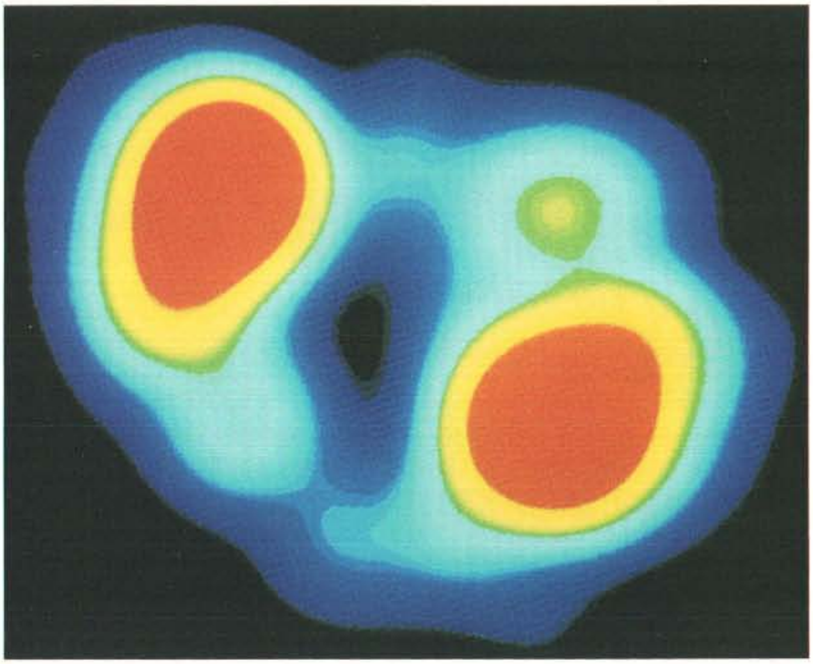
By investigating such rings, astronomers may be able to make precise measurement of how quickly the universe is expanding. Because a gravitational lens magnifies the size and intensity of the source, they may also get a good look at the distant galaxy.

The Einstein ring observed by Jauncey and his co-workers is only the third to have been discovered. In addition to the ring, the object, known as PKS1830-211, has two bright spots. (The false-color image below was produced by the MERLIN radio telescope in the U.K.) "Honestly," Jauncey exclaims, "it looks like two egg yolks frying in a ring of white." The yolk is believed to be the center of an extremely distant galaxy whose image has been split by the gravitational field of a closer object. The ring, Jauncey says, is the contorted image of a luminous jet that protrudes from the galactic center.

Until recently, PKS1830-211 had not been studied in detail, because most of the radiation that it emits is obscured by our own galaxy. But by employing a battery of radio telescopes in Australia, India, the U.K. and the U.S., Jauncey and his colleagues were able to resolve the fine structure of the object. They reported in *Nature* that PKS1830-211 is 100 times brighter than either of the other two known Einstein rings. It also appears to be brighter in the radio region than all but five other compact celestial bodies.

Jauncey and his co-workers are not sure why the ring shines so brightly. On the one hand, the background object could be a luminous galaxy, such as a quasar. On the other hand, the foreground object could be amplifying the light from a distant and dim partner. But neither explanation could be described as stellar. It is unlikely that a particularly bright galaxy is aligned with a gravitational lens. It is also improbable that a gravitational lens could greatly enhance the brightness of the source.

In either case, observations of this brightest Einstein ring should provide fundamental insights into cosmology and gravitation. Only a scientist could turn distortion into truth. —*Russell Ruthen*



rectly examine whether the stem cells can give rise to specific subsets of cells, such as critical immune system cells known as *T* and *B* cells.

Baum and Weissman claim they have a more direct demonstration of true stem cell activity. Like Moore, they first screen out differentiated blood cells with antibodies. Unlike Moore's team, they do not use *kit* ligand.

When the West Coast researchers made antibodies to the *kit* ligand, they uncovered evidence that it does not bind to all stem cells—or only stem cells. "We found that most but not all mouse stem cells bind to *kit* antibodies," says Weissman, one of the founders of Systemix and a member of a team that three years ago isolated stem cells in mice. "But several types of nonstem cells do bind to *kit* antibodies. Response to *kit* ligand is not sufficient to identify a stem cell."

Baum's technique for testing stem cells relies on a strain of genetically defective mice known as SCID mice, which lack the ability to form *T* and *B* cells. Because they have no immune system, human blood-forming tissues—bone marrow and thymus gland—can be transplanted into them. Baum and his colleague Bruno Péault injected candidate human stem cells into transplanted bone marrow and thymus and found that they gave rise to all the normal cellular components of blood.

Genetic markers proved that the blood cells were indeed derived from the human stem cells. "The final assay for a stem cell is that it can give rise to all lineages and self-renew more stem cells," Weissman declares. "Baum has isolated a candidate human stem cell that fulfills all the criteria."

The contrasting approaches of the two groups do not mean that one of them must be wrong: both may have developed methods for purifying stem cells to a useful degree. The proof will be in how well the cells perform at rescuing critically ill patients.

Such tests may begin soon. Moore, for his part, has already shown in animal experiments that using *kit* ligand to sort bone marrow cells promotes the regrowth of all types of blood cells after they are transplanted into bone marrow. He is now experimenting with *kit* ligand to boost stem cell numbers in the blood: he hopes to develop ways of harvesting stem cells to treat patients without tapping the bone.

Systemix has patented its method and hopes to use it on a patient undergoing a blood replacement procedure, properly known as autologous reconstitution, as early as the end of the year. —*Tim Beardsley*

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Has AIDS Peaked?

Questions persist in modeling the deadly, atypical infection

Predictions for the incidence of AIDS made in the mid-1980s were gloomy, suggesting an accelerating spread of the deadly epidemic well into the 1990s. Now the trend seems to be heading in the other direction. The numbers, however, may not tell the whole story.

The latest figures from the Centers for Disease Control show an increase of about 9 percent in the number of new AIDS cases reported, from 41,000 in 1989 to about 44,500 in 1990. The increase in 1989 was about 17 percent and the year before about 24 percent. "The diagnoses are not increasing as rapidly as they were several years ago," says John Karon, a CDC statistician.

But whether a plateau is near, he adds, "is impossible to say. We've seen temporary plateaus before." Indeed, making predictions about the epidemic—and hence about the future health costs to the nation—is filled with unknowns. The virus has a long incubation period; only half the HIV-infected population exhibits symptoms within 10 years. And the very way the disease is defined, as a regime of specific opportunistic infections, may be skewing the statistics.

Not surprisingly, many AIDS cases are incorrectly diagnosed, and perhaps 10 to 15 percent are never reported to the CDC. Underreporting may be highest among the urban poor, a group in which the disease is still spreading rapidly. Among them, misdiagnosis is highest among women, who are now the fastest-growing group with AIDS. Cases in women increased by more than 30 percent from 1989 to 1990, and bigger jumps for 1991 seem likely.

Some independent studies do support the CDC numbers. To predict when the incidence of AIDS might level off, Joel W. Hay, a health economist at Stanford University, and his colleague Frank A. Wolak applied an approach called back-calculation. The method uses data on current AIDS incidence and incubation to reconstruct HIV infection rates in the past and then to project cases in the future. Hay and Wolak calculated that the epidemic is now peaking. Adjusting for reporting delays, they predict about 47,000 to 67,000 AIDS cases for 1991.

"We're seeing a tremendous slowdown in the growth of AIDS cases," Hay says. The declining rate of AIDS is consistent with the notion that most HIV infections occurred before 1986. According to Hay, HIV infection rates dropped sharply thereafter because those at high risk had already contracted the disease and those not at risk had begun to take precautions.

But Ronald Brookmeyer, a statistician at Johns Hopkins University, is less optimistic. Studies such as those by Hay and Wolak "have not corrected for the effect of treatment," Brookmeyer maintains. So he assigned a certain degree of efficacy to therapeutic drugs such as AZT and pentamidine, which should push the plateau into the future because they delay the onset of symptoms. His report, published in *Science,* concludes that the epidemic will level off during the next five years, with about 60,000 to 67,000 new cases each year. The CDC plans to publish its own projections through 1994 by the beginning of September.

Still, none of these projections may accurately reflect the future. The statisticians used numbers based on the CDC's definition of AIDS. But the indicators marking an AIDS diagnosis are based primarily on symptoms displayed by homosexual white men, such as Kaposi's sarcoma and *Pneumocystis carinii* pneumonia. Women, who make up about 10 percent of all cases, frequently come down with different initial symptoms. In females, HIV infection has been associated with acute pelvic inflammatory disease and cervical cancer.

Particularly hard hit will be poor minority women. Because they may be ill and not meet the current diagnosis of AIDS, these women may not qualify for Social Security benefits or treatment. "If you are a woman of color, you are less likely to get medication," says Kenneth H. Mayer, director of the AIDS program at Brown University. "It's the feminization of poverty."

"The CDC has to rethink its definition," Mayer adds. Indeed, the American Medical Association has recently requested that the CDC reconsider its definition of AIDS. "We were fearful that the definition could be too narrow," says M. Roy Schwarz, the AMA's senior vice president of medical education and science.

AIDS Education May Breed Intolerance

Two thirds of Americans would be concerned about sharing a bathroom with someone who has AIDS. One third would not lend their tools to an infected co-worker. Proximity and casual contact, of course, are not considered to be vectors for the spread of the disease. So education about the modes of transmission and known risk factors should be the best weapon against such worries.

Not necessarily, say researchers at the Georgia Institute of Technology. David M. Herold and John M. Maslyn, who study organizational behavior, believe a little education may be worse than no education at all. They found that some AIDS education programs made workers less tolerant of those with the disease.

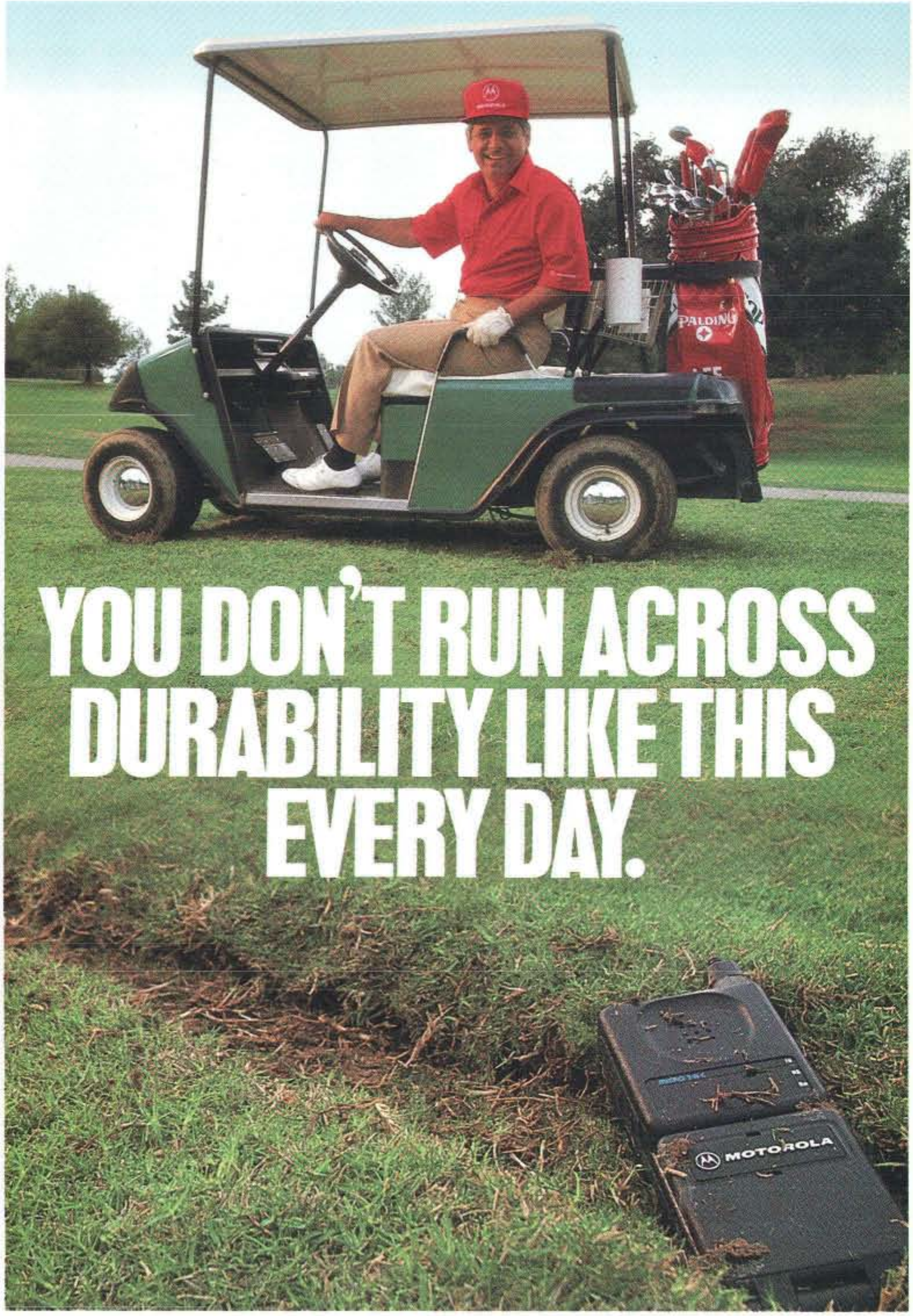
The main culprits were programs that provided only a brochure or a presentation from an outside expert that lasted less than 45 minutes. Unfortunately, such education makes up more than half of all types of AIDS schooling in the workplace, according to the study. In contrast, longer programs, those lasting more than two hours, improved the attitudes of employees.

The problem, the researchers say, stems from the educational materials published by public health organizations. These pamphlets emphasize behavioral changes that would reduce the risk of infection. "Most education materials just show little blood cells being attacked by little monsters," Herold observes. And short corporate education sessions never discuss "how to be supportive and deal with others." Employees come away with a "Now-that-I-know-how-you-get-it, why-should-I-help-you attitude," Herold says.

Credibility is also an issue. The study found that 45-minute presentations could improve attitudes, but only if they were given by in-house spokespersons. Insiders, Herold notes, are better able to address fears specific to that workplace.

Providing information about AIDS to workers is "crucially important," Herold asserts. Most problems do not come from those with AIDS but from other workers "who raise hell with their supervisor." Moreover, as improvements in treatment allow infected people to remain healthy longer, Herold notes that more businesses "are going to have to confront the issue of workers with AIDS."

—Philip Yam



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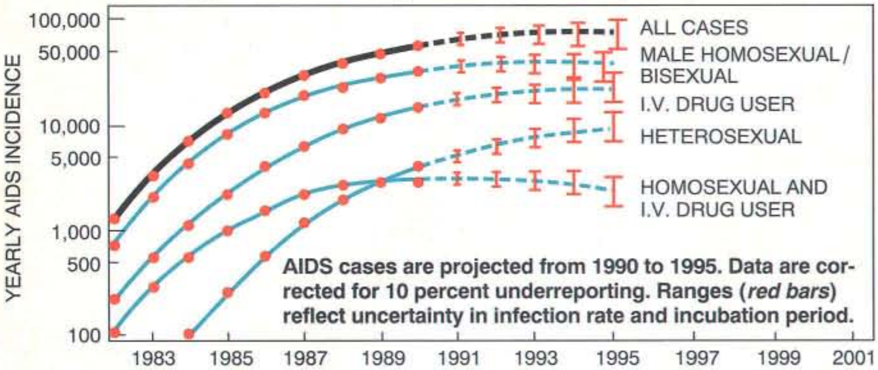
Signs of Slowing in the AIDS Epidemic



SOURCE: Ronald Brookmeyer

Instead of just adding to the list of opportunistic infections, the CDC is considering a different approach. One proposal on the table is to classify individuals with fewer than 200 CD4 *T* cells per cubic millimeter as having AIDS. Such cells, also known as helper *T* cells, mobilize the rest of the immune system. Healthy individuals have about 1,000 such cells per cubic millimeter of blood.

Adding the cell count to the definition would dramatically increase the number of AIDS cases. The CDC estimates one million Americans to be HIV positive. According to Brookmeyer's calculation, 265,000 of them would be classified as having AIDS right now. "That's more cases than we've seen to date," Brookmeyer observes. As a result, AIDS cases would not level off but increase by 40 percent over the next five years.

All these factors make determining the extent of AIDS a tricky business. "Once you change definitions," Brookmeyer sighs, "the numbers become a real bear to interpret." —*Philip Yam*

Model Mice

Transgenic animals aid Alzheimer's research

There is no shortage of theories about what causes Alzheimer's disease, but there is a definite dearth of models for studying it. Most clues about this devastating neurological disorder, which afflicts four million Americans, have been gathered after the fact—by studying the brains of the deceased. At the moment, this is the only sure means of diagnosing the condition assumed to be present when patients lose the capacity to think and remember.

Mice that contain genes for human beta-amyloid protein may soon provide researchers with a means of studying the disease while it is in progress. The role of so-called beta-amyloid plaques that are found in the brains of Alzheimer's patients is controversial. The plaques are also found in the brains of many normal elderly people, but in seemingly healthy bodies they are free of the surrounding tangles of dead and dying neurons associated with Alzheimer's disease.

The transgenic animals were first described in mid-July in *Nature* by Barbara Cordell and her colleagues at California Biotechnology (Cal Bio) in Mountain View. Simultaneously, a team from the Miles Research Center in West Haven, Conn., led by Dana Wirak, reported its achievement in *Science*. (Miles is a subsidiary of the German company Bayer AG.) A third group, at the University of California at Irvine, is expected soon to report development of its own line of amyloid-expressing mice.

The researchers are waiting to see how the plaques and surrounding brain tissue change as the mice age and whether the creatures go on to display neuronal cell death or degeneration of the central nervous system. "The models are exciting from the point of view of aging and testing whether they will develop other features of Alzheimer's disease," comments Peter Davies, professor of pathology and neuroscience at the Albert Einstein College of Medicine in Bronx, N.Y.

If amyloid deposition does prove to be involved in the disease—rather than a mere by-product of another, as yet unknown, destructive process—Cal Bio's mouse could certainly be used for drug screening, Davies observes. Cal Bio's mice have developed amyloid deposits that look very much like those seen in human brains in early stages of Alzheimer's disease.

Cordell believes the plaques formed because her team inserted into mouse eggs the gene for the amyloid precursor protein (APP), which later gives rise to beta-amyloid. Precursors are thought to contain the genetic instructions that tell cells how to assemble a given protein. In contrast, the Miles scientists inserted a smaller genetic sequence coding for the amyloid protein itself. "We opted for an earlier step that we think asks a larger question," Cordell says.

The California company chose one of several identified forms of precursor, this one called 751, which was shown last year to be expressed in humans in both the brain and other parts of the body. Certain other forms of the precursor appear in the brain only, but Cordell chose the form she did because "there seems to be some correlation between the overexpression of 751 and deposition of beta-amyloid." Indeed, the same areas of the human brain that become riddled with plaques, the hippocampus and cortex, are also afflicted in the Cal Bio mouse models.

The Miles mouse expresses the full beta-amyloid protein within hippocampal cells only, and the 42-amino-acid sequence remains contained within those cells instead of pushing through to form conglomerates of plaque. Still, Wirak asserts, the model should be sufficient to investigate some important basic questions: Is beta-amyloid protein neurotoxic, and will it induce the deterioration associated with Alzheimer's? If it accumulates in the cell, can it get out, and if so, by what mechanism?

Wirak will begin putting mice through learning experiments this fall to build up their stores of memories. "Over time, we'll look closely at the brain for the appearance of extracellular plaques, examine the composition of those that are formed and watch for the intervention of other neurons," he says. If this line of mice or others prove to be valid models, Wirak intends to perform the experiment on rats, "because they're smarter."

Cal Bio and its partner Daiichi Seiyaku clearly have commercial intentions. "If the mice are representative of Alzheimer's disease, we ultimately hope to use them to screen potential therapeutics," declares W. Virginia Walker, Cal Bio's vice president for finance. The *Nature* paper revealed a fair amount of detail as to how the mice were made, Walker notes, so other groups will be able to follow the approach. See how they run. —*Deborah Erickson*

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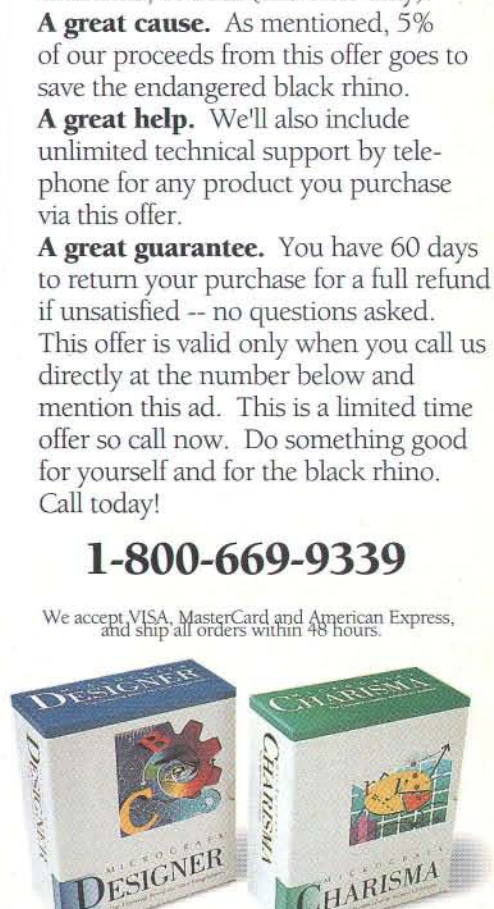

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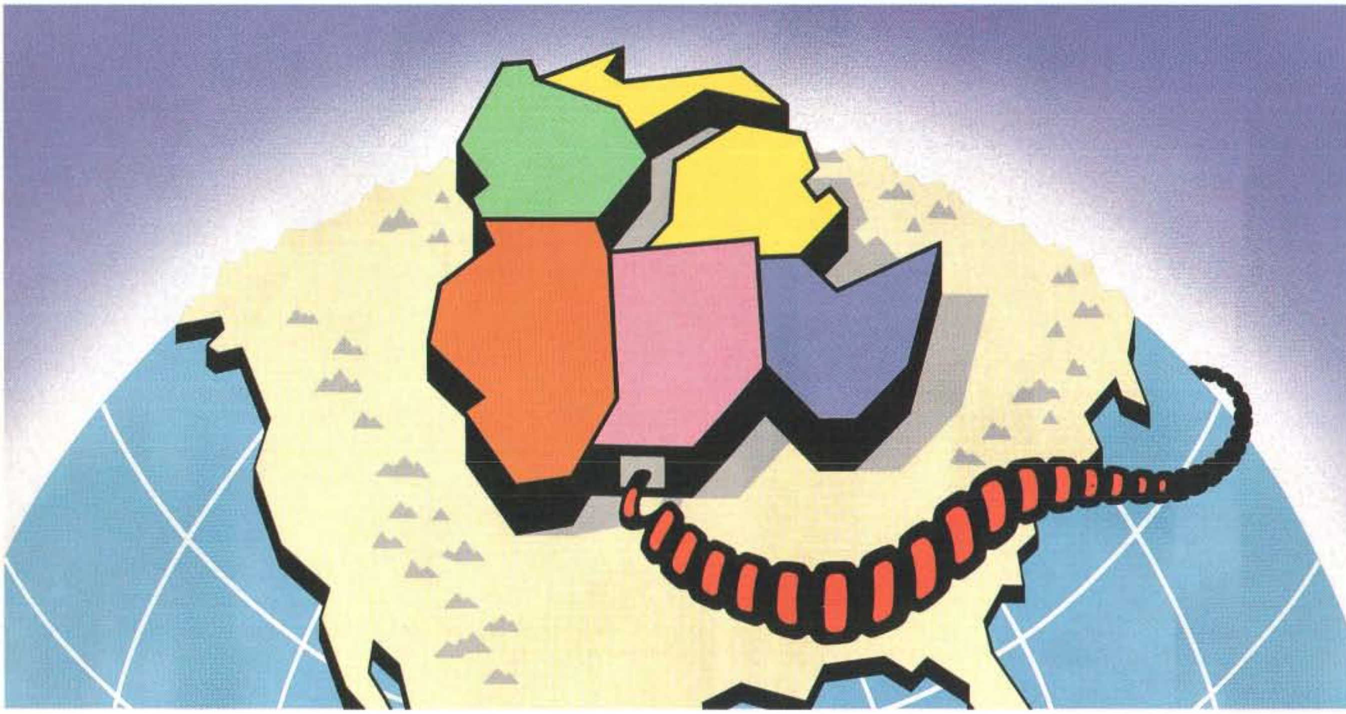

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Psychic *vs.* Skeptic

A spoonbender sues his arch critic for libel

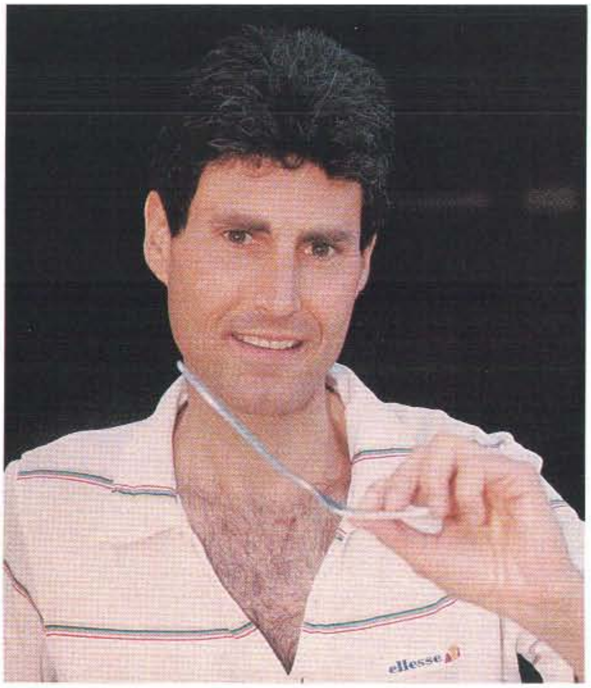
For 20 years, Uri Geller, the man sometimes hailed as the "World's Greatest Psychic," has left a trail of bent spoons as proof of what he claims are his paranormal powers. He has made a career out of deforming small metal objects, starting broken watches, levitating people and reading minds by methods he calls psychokinesis and telepathy. For almost as long, James Randi—alias "The Amazing Randi"—an accomplished magician and investigator of the occult, has pointed out that Geller's feats can apparently be duplicated by any competent conjurer.

This past May, Geller and his attorneys filed a $15-million libel suit against Randi and the Committee for the Scientific Investigation of Claims of the Paranormal (CSICOP), an organization that Randi helped to found. Geller has expressed in print a willingness to press more actions, in other countries if necessary, "to stop [Randi] from spreading lies about me." Many skeptics of the occult are concerned that Geller's campaign against Randi could have a chilling effect on future attempts to debunk the supernatural.

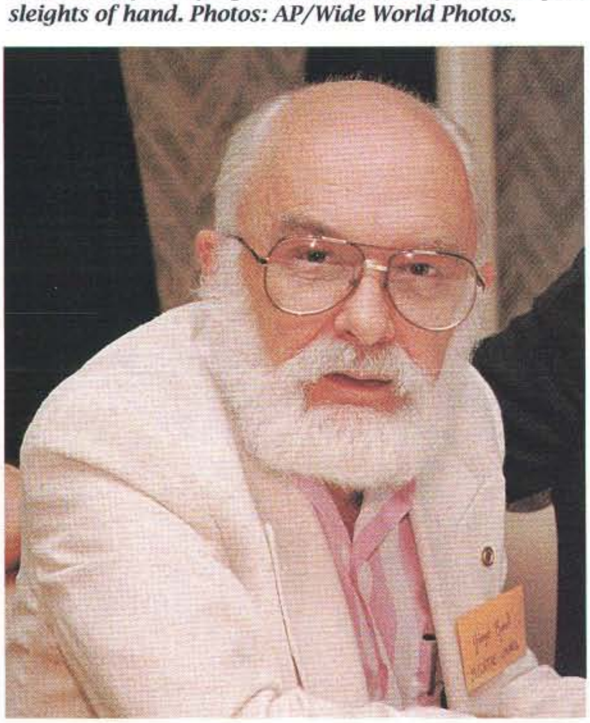
Geller's current lawsuit charges that in an interview published on April 9 in the *International Herald Tribune,* Randi made false and defamatory statements about Geller. In one passage, Randi is represented as stating that during scientific tests of Geller's abilities, the showman had deceived researchers who were not well versed in magic tricks. Another passage quotes Randi as saying that Geller's feats "are the kind that used to be on the back of cereal boxes when I was a kid. Apparently scientists don't eat cornflakes anymore."

Those statements clearly outrage Geller. "It's bad enough that he's attacking my abilities," he complains, "but he's also attacking my originality. Before I was born, I am almost 100 percent sure there was no such thing as spoon bending." He goes on to say, "I'd like a judge to see those cereal boxes."

"Both those statements are true, and I can support them," Randi retorts. He claims to have affidavits from magician organizations affirming that many of Geller's stunts are "very simple tricks that kids have been doing for ages. They literally were on the backs of cornflake boxes." Randi and other members of CSICOP have publicly performed metal bending and other seemingly telekinetic skills on many occasions to prove that no paranormal abilities are required.



URI GELLER **(above)** ***is famous as a psychic for bending spoons. Now he is suing the magician James Randi*** **(below)** ***for saying that his mental feats are just sleights of hand. Photos: AP/Wide World Photos.***



Robert Steiner, a co-founder of the Bay Area Skeptics in San Francisco and a former president of the Society of American Magicians, has watched Geller perform. He agrees with Randi's opinion of Geller's talent. "Please understand that I'm not putting him down as a performer," he says. "He's skilled, he's creative, but there's no evidence that it's supernatural."

"If I were doing something by trickery, I should have been caught a long time ago," Geller insists. "I've done hundreds of television shows, hundreds of radio shows; thousands and thousands have seen me. No one has ever said to me, 'Here is a film and you've been caught red-handed.'"

Actually, Randi claims that he can do exactly that. He says that on a videotape of the showman filmed in Italy he can point to Geller making the exact sleights of hand a magician would use to conceal and then gradually reveal a bend in a spoon. "It's absolute video proof," Randi says. "The evidence can and will be produced in court."

Geller makes no promises about demonstrating his powers in front of a judge. "I cannot do it on command," he says. "I am not a radio or a television that you turn on or off." He argues, however, that the paranormal is not at issue: he believes Randi's statements constitute an unlawful defamation of his character and of spoon bending, his trademark.

To win a libel suit under U.S. law, a plaintiff must usually prove that the defendant made a false statement of fact, either maliciously or with reckless disregard for the truth. If the plaintiff is a public figure, proof that the falsehood caused real injuries must also be presented. In this instance, Geller may have to prove that he did not trick scientists, that his act is original and that he has suffered actual damages because of Randi's statements. If Randi has evidence to the contrary and if Geller is unable to demonstrate his abilities or losses to the court, Geller may have a difficult time making his case.

Yet even if he loses, Geller could still come out ahead. Twice before, he has tried unsuccessfully to sue Randi for libel; both cases were thrown out on technical grounds—"with prejudice against Geller," according to Randi. Victory did not come cheap, however: Randi says he spent more than $155,000 defending himself against those charges. In an open letter published this past May in *BASIS*, the newsletter of the Bay Area Skeptics, Randi wrote: "Should these actions continue, I will be forced into silence from my inability to support further legal costs." His lawyers are investigating whether his defense costs can be reclaimed from Geller, he says.

In the meantime, those skeptical of the existence of the supernatural have rallied to Randi's cause. Steiner recently opened a defense fund to help Randi defray his legal expenses. According to Randi, the fund would also be used to defend other skeptics who found themselves in a similar plight.

Many skeptics worry that more proponents of the supernatural will follow Geller's precedent. Even the threat of a lawsuit could prevent some critics from speaking their minds. And regardless of the outcome of *Geller* vs. *Randi*, the case has already deprived CSICOP of Randi's services as a debunker: in May he resigned from the organization to protect it from being named in any future suits against him.

"CSICOP is deeply concerned that libel suits such as this can be used to silence open debate on important scientific issues," says James E. Grossberg, the lawyer representing CSICOP. "If people can't comment on claims of miracles, we're in real trouble," Steiner agrees.

"If the intent of these lawsuits is to interfere with my First Amendment rights, then it has been a failure," Randi says flatly. "I have the right to make comments on what I know to be the truth." He adds that "the direct question that should be asked of [Geller] is, 'Do you have psychic powers? And if so, have they ever been demonstrated?' And the answer to both those questions is no." —*John Rennie*

Mutt & Jeff

Did Cro-Magnons and Neanderthals coexist?

Judging from the fossil record, Neanderthals were short and powerfully built; Cro-Magnons were tall and lanky. Modern Europeans? Well, they are a little like one and a lot like the other. Who were the progenitors of the first modern humans in Europe?

Anthropologists are sharply divided over that question as well as over exactly where and when modern humans first appeared. At the heart of the controversy lies the Neanderthal question: Did they represent a doomed offshoot of the hominid line, or were they instead an integral part of the ancestry of modern-day Europeans? The latest dating of a Neanderthal skeleton from Saint-Césaire, France, makes the debate even more intriguing.

A group of French geologists headed by N. Mercier of the Centre des Faibles Radioactivités, used thermoluminescence methods to date burnt flint tools found near the skeleton. Their data, reported in *Nature*, indicate that Neanderthals survived in Europe as recently as 36,000 years ago.

That places them there several thousand years after the date many anthropologists believe modern humans arrived in western Europe. "A picture is beginning to emerge of a complex and dynamic period of transition at the in-

SKULL from a Neanderthal that lived some 36,000 years ago at Saint-Césaire, France. A cranial fragment* (top) *from an older fossil is for comparison. Photo: Chester Tarka, courtesy of Bernard Vandermeersch, University of Bordeaux.

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terface between the last Neanderthals and first modern humans in Europe," wrote Christopher B. Stringer of the British Natural History Museum in a commentary accompanying the French team's report.

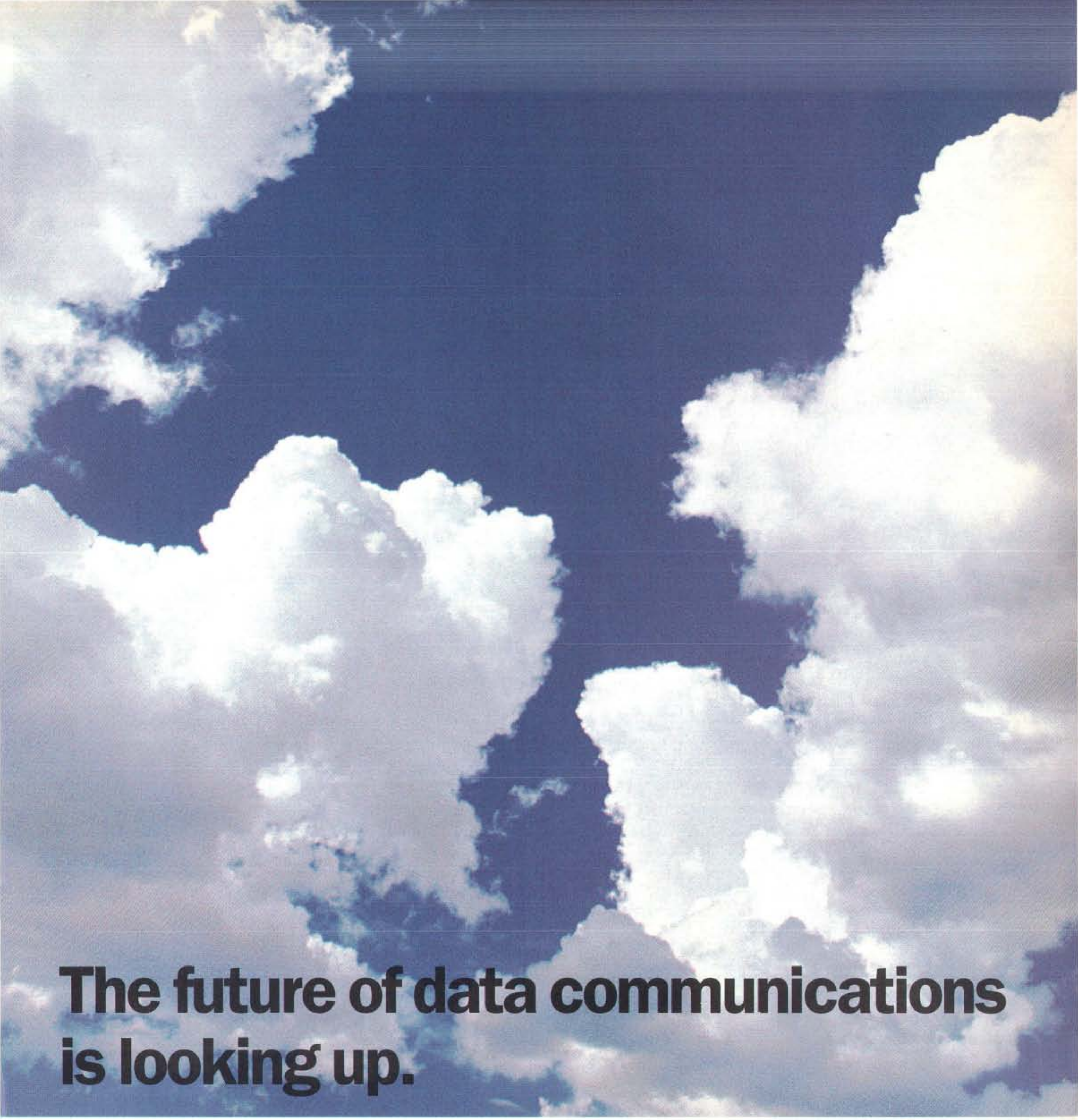
If the two groups were coinhabitants, they may also have been cohabitants. Still, Stringer notes, there is little evidence of a genetic contribution from Neanderthals in modern Europeans. He maintains that the new dating provides additional support for the "out of Africa" theory he proposed 10 years ago on the basis of his interpretation of the fossil record.

Stringer is keen to show that Neanderthals coexisted with modern people in western Europe as well as in other places along the route that leads from Africa. If the early modern human archaeological sites are progressively more ancient closer to Africa, that trend would support the idea of an African genesis. Indeed, the earliest skeletons attributed to early modern humans, in modern-day Israel, are found within a few miles of roughly contemporary Neanderthal fossils.

Side by side, the two populations are as different as stocky wrestlers and lanky basketball players. The contrast suggests differing adaptations to climate: tall bodies are easier to cool and thus are commonly associated with warm regions. "Neanderthals are clearly cold adapted," Stringer says. "Early modern humans look as if they walked straight out of Africa."

Geneticists gave that idea crucial support in the late 1980s, when a group led by Allan C. Wilson of the University of California at Berkeley compared the genes of living people from around the world to infer their common descent from an African woman—"Eve," as it were. They knew they had traced a woman because they studied genes encoded on mitochondrial DNA, inherited from the mother alone. By using the DNA as a molecular clock, the Berkeley group was able to date Eve to between 100,000 and 150,000 years ago.

The problem, Stringer says, lies in demonstrating that the very earliest modern humans were present in western Europe as early as 40,000 years ago, not to mention that they were tall and gracile. The earliest Cro-Magnon fossils have come from individuals who lived perhaps 25,000 years ago. The only evidence of earlier habitation lies in archaeological evidence generally associated with modern humans, the so-called Aurignacian tools—long, thin blades fashioned from flakes knocked off a prepared flint core. "Wherever we've got the Aurignacian technology,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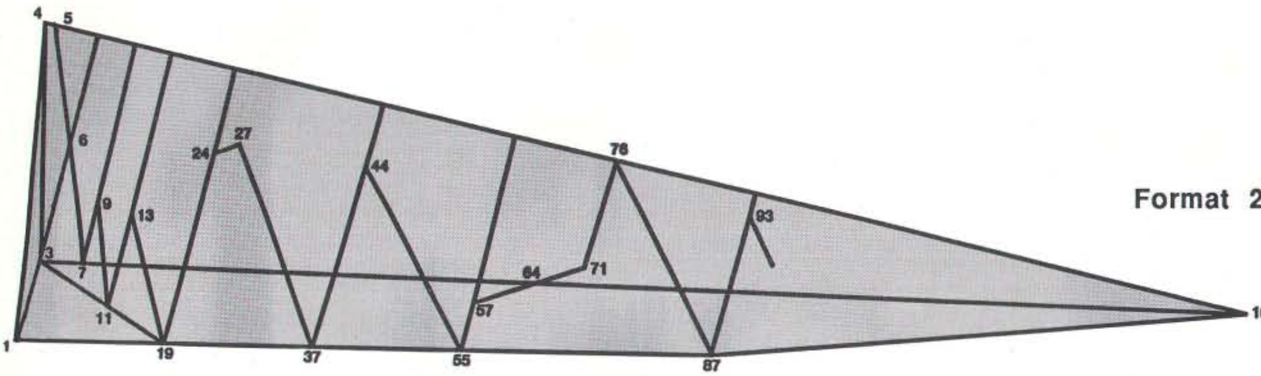
Format 261 is based on a truss and scaffold conjoint array of the Elements. It belongs to the family of Coler Engineering Formats which includes the Signature of the Elements of Format C_{51} (E.g., Scientific American, March, 1991, p. 121, ad). Format 261 is a closed convex polygon which we call a "Scrimshaw."

The Scrimshaw is proving to be surprisingly useful in solving engineering problems involving new materials and their fabrication.



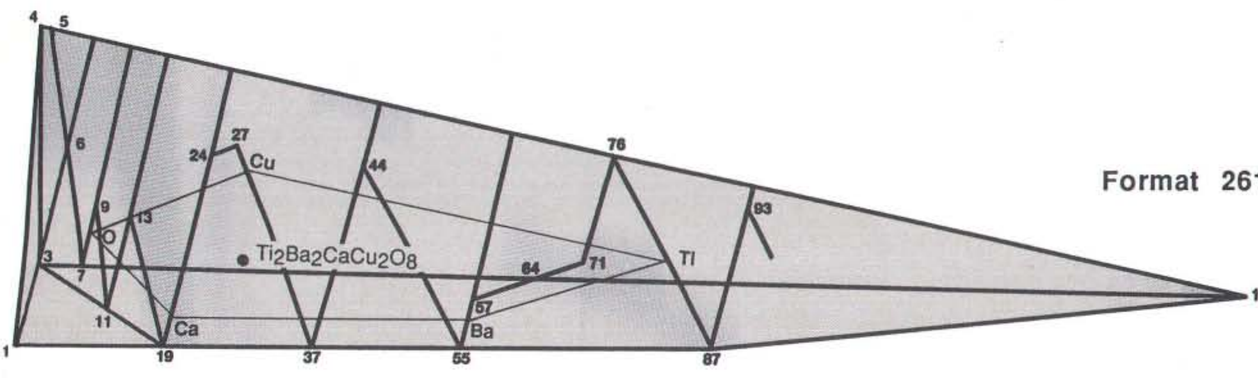
Format 261

The parallel conjoints through 1:3:6, 7:9, 11:13, 19:24, 37:44, 55:57, 71:76, and 87:93 are orthogonal to the conjoint 4:5:76:168 and provide some insight regarding perceived periodicity patterns.

Archimedes Points

Archimedes solved mathematical problems by mechanics and vice versa. Every composition of matter can be characterized as an assembly of one or more elements, and the proportions by number of the respective atoms.

An Archimedes Point, as we define it, for a composition of matter per Format 261 would approximate the center of gravity of the polygon connecting the elements of the composition and weighted according to the number of atoms at the respective vertices.

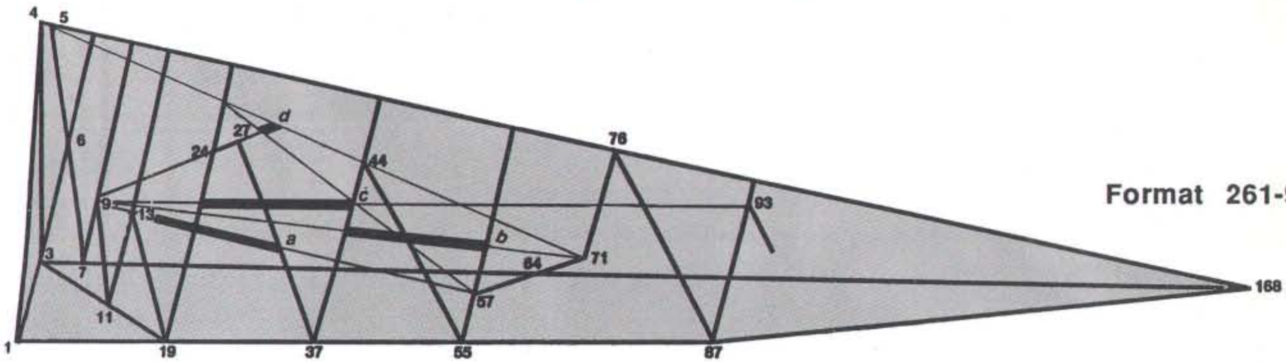


Format 261-4

Format 261-4 indicates the approach for fixing the Archimedes Point for the superconductor designated as $Ti_2Ba_2CaCu_2O_8$ and marked by the solid circle.

Every real composition that we here conceive of has an Archimedes Point within the Scrimshaw. There is no composition outside the Scrimshaw.

Certain Superconductor Classes



Format 261-9

Format 261-9 shows exploratory use of Format 261 in work with four classes of cognate superconductors.

The thin lines are truss-web members. The thick segments are superconductor domains of concentration of the respective Archimedes Points of which

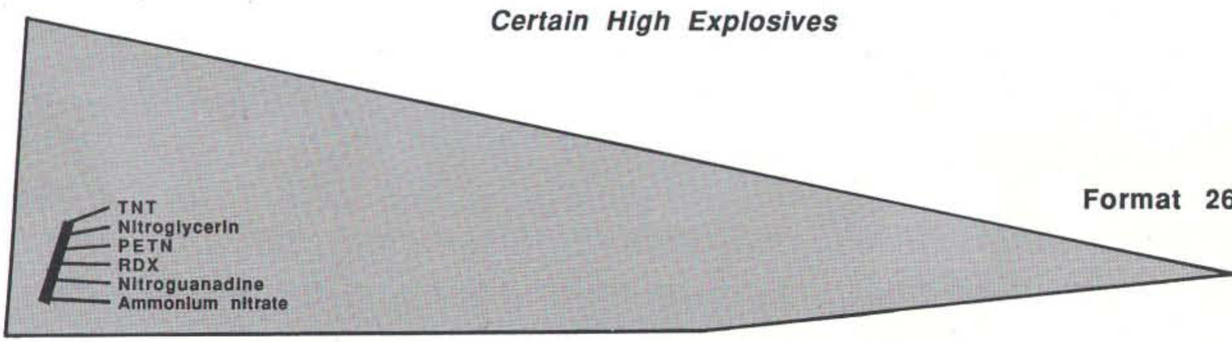
> ***a** is based on all compounds presently known to us with T_c values $\geq 30^o$ K. No exceptions are known. This class of compounds seems to require at least four elements.*
>
> ***b** is based on major Chevrels.*
>
> ***c** covers the class of the present essential materials relating to Nb:Ti.*
>
> ***d** includes all the Archimedes Points corresponding to Rh_4B_4L, where L is a Lanthanide.*

The Lanthanide conjoint 57:71 seems to be of unusual guidance value. In other formats involving movable linkages, a Lanthanide link pivoting on Gd is singularly interesting.

All the webs of the segments conjoin on fluorine.

The applications of the Coler Engineering Format Calculus are not limited to superconductors. Thus, e.g., an exploratory for certain high explosives:

Certain High Explosives



Format 261-19

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we've got modern humans with it," Stringer says.

He also sees traces of modern people in the casts, or pseudomorphs, their bodies are thought to have made before disintegrating in the earth. Such casts suggest that six-footers walked the plains of Spain at the same time the much shorter Neanderthals were living at Saint-Césaire. If the morphology of a people does imply a response to the climate, then the early modern Europeans seem to have recently left a warm abode for a colder one.

In fact, the bodies of early modern Europeans are more "Africanized" than those of contemporary Europeans, according to Erik Trinkhaus of the University of New Mexico and his graduate student Trenton Holliday. They measured the proportions of modern Europeans from Cro-Magnon times to the Middle Ages and found that an originally gracile build became less so, essentially reaching the modern average around 20,000 years ago.

None of these arguments about tools, bones and body casts makes any impression on Milford H. Wolpoff of the University of Michigan. Wolpoff, perhaps the most vociferous critic of the African origins theory, says "the juxtaposition of industries and moderns is so confused that you'd be sticking your neck out—you'd be foolish—to identify them by their tools." He adds that even if the two species did coexist, they may well have split off from an earlier Neanderthal population in eastern Europe, where fossils showing transitional, or interbred, populations have been found.

Wolpoff denies that the gracility of early modern Europeans proves African ancestry, arguing that climate is not necessarily the sole influence on body proportions. "Some of us think that more mobile people have longer legs," he says, noting that Cro-Magnon traders ranged far more widely than had the Neanderthals. "Take the Masai of East Africa—some of the tallest, lankiest people alive. Living right next to them, interacting with them, sometimes working for them, are the Pygmies—the shortest people in the world. Pygmies don't walk long distances."

Even so, the new evidence of coexistence between the early human species is an important piece of the puzzle, despite the disagreement among anthropologists about what it proves. The observation may help put to rest the once widely espoused theory that modern humans swept in, murdering Neanderthals as they went. In his commentary, Stringer concludes that "the Neanderthals probably went out with a whimper, not a bang." —*Philip E. Ross*

Clear Advantage

Opaque gases can be made transparent using laser light

What if you had the power to see through opaque materials? Recent experiments suggest the possibility is not so remote, at least for gases. Investigators at Stanford University and the University of Toronto have devised a way to make atomic vapors transparent to light that they normally absorb. The technique is unlikely to allow people to peer through walls, but it may play an important role in laser and optical technologies.

To make opaque gases transparent, Stanford physicist Stephen E. Harris and his co-workers Klaus J. Boller and Atac Imamoǧlu were able to coax atoms to cough up photons they would ordinarily devour. The researchers first demonstrated their technique in a gas produced by vaporizing solid strontium, which is opaque in the ultraviolet region of the spectrum. Strontium atoms ordinarily let through only two ultraviolet photons per billion, absorbing the rest.

The Stanford team bathed the strontium gas in green laser light. The green light alters some of the atoms in such a way that they no longer absorb ultraviolet radiation. As a result, the gas transmits nearly 40 percent of the ultraviolet radiation.

In the absence of green light, when a strontium atom absorbs a photon of ultraviolet radiation, its energy increases by a discrete amount. From this high energy level, the atom will almost always release an electron, whereby the energy of the ultraviolet photon is dissipated. But every so often, the high-energy atom will emit a photon of either ultraviolet or green light. By releasing an ultraviolet photon, the atom falls back to the original energy level; by emitting a green photon, it stabilizes at an intermediate energy level.

Shining the green laser light on the gas introduces an electromagnetic field that shifts the energy levels so that the difference between the intermediate level and the high level is close to zero. If an ultraviolet photon passes near the altered atom, it has enough energy to cause the atom to jump from the first state to either the new intermediate level or the new high level. But because the two levels are so similar, they compete for the photon and interfere with each other. Consequently, the atom is unlikely to reach either of the high-energy states, and it will fail to capture ultraviolet photons.

This quantum mechanical effect is known as Fano interference. In the 1960s Ugo Fano theorized that interference effects could elicit transparency in atoms and gases. Harris and his colleagues are the first to demonstrate that light is indeed an effective means for conjuring up Fano interference and for making opaque gases transparent. "The idea was staring us in the face, but we didn't latch on to it until recently," comments Boris P. Stoicheff, who is also studying light-induced transparency at the University of Toronto.

By choosing appropriate wavelengths of laser light, both Harris and Stoicheff have been able to clarify gases not only of strontium but also of hydrogen and lead. "It is possible in principle to apply this technique to molecular vapors, liquids and solids," Stoicheff remarks. Harris is a bit more cautious. "I don't think our work is a first step in getting light through complicated materials."

But both researchers agree that the transparency technique could help them develop a new type of laser. Almost all laser media are energized in such a way that more atoms are kept at a high energy level rather than at a low one. The high-energy atoms stimulate the emission of light, whereas the low-energy ones gobble up photons.

The transparency technique could reduce the losses associated with low-energy atoms because it could prevent such atoms from absorbing light. The technique might lead to lasers that require relatively few high-energy atoms to generate a beam. Such lasers would need little power and would be able to produce light over a wide range of frequencies. "There has been extensive theoretical work" on this kind of laser, Harris says, "but experiments are just beginning."

Stoicheff has also recently shown that it is possible to exploit the transparency technique to improve the performance of components known as nonlinear optics. These devices, which are used in a variety of laser systems, combine several colors of light to generate radiation of a different color. But the components are often inefficient and produce very little light of the desired color. These problems can be overcome with light-induced transparency because materials that strongly absorb radiation can efficiently combine certain wavelengths of light, provided the absorption is suppressed.

Harris and Stoicheff are not certain whether their transparency technique will ever have practical applications. After all, they can see only through gases, not into the future. —*Russell Ruthen*

PROFILE: DAVID A. HUFFMAN

Encoding the "Neatness" of Ones and Zeroes

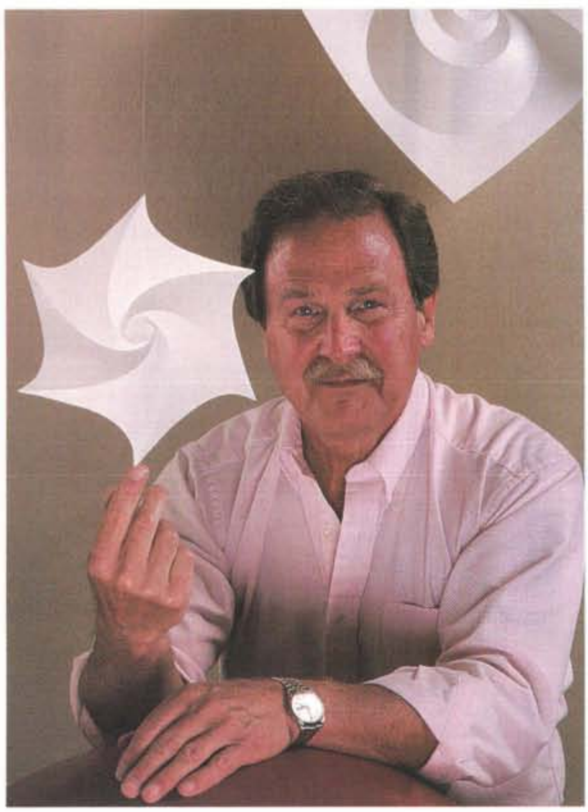
Large networks of IBM computers use it. So do high-definition television, modems and a popular electronic device that takes the brain work out of programming a videocassette recorder. All these digital wonders rely on the results of a 40-year-old term paper by a modest Massachusetts Institute of Technology graduate student—a data compression scheme known as Huffman encoding.

In 1951 David A. Huffman and his classmates in an electrical engineering graduate course on information theory were given the choice of a term paper or a final exam. For the term paper, Huffman's professor, Robert M. Fano, had assigned what at first appeared to be a simple problem. Students were asked to find the most efficient method of representing numbers, letters or other symbols using a binary code. Besides being a nimble intellectual exercise, finding such a code would enable information to be compressed for transmission over a computer network or for storage in a computer's memory.

Huffman worked on the problem for months, developing a number of approaches, but none that he could prove to be the most efficient. Finally, he despaired of ever reaching a solution and decided to start studying for the final. Just as he was throwing his notes in the garbage, the solution came to him. "It was the most singular moment of my life," Huffman says. "There was the absolute lightning of sudden realization."

That epiphany added Huffman to the legion of largely anonymous engineers whose innovative thinking forms the technical underpinnings for the accoutrements of modern living—in his case, from facsimile machines to modems and a myriad of other devices. "Huffman code is one of the fundamental ideas that people in computer science and data communications are using all the time," says Donald E. Knuth of Stanford University, who is the author of the multivolume series *The Art of Computer Programming.*

Huffman says he might never have tried his hand at the problem—much less solved it at the age of 25—if he had known that Fano, his professor, and Claude E. Shannon, the creator of information theory, had struggled with it. "It was my luck to be there at the right time and also not have my professor discourage me by telling me that other good people had struggled with this problem," he says.



DAVID A. HUFFMAN expresses mathematical theorems in intricate paper sculptures. Photo: Matthew Mulbry.

Like many codes, including the one named after Samuel Morse, Huffman's creation tried to find a way to assign the shortest codes to those characters used most, the longest codes being reserved for those used rarely if at all. This process was carried out by forming a so-called coding tree, in which the probability that a number, letter or another character will occur is designated as a leaf on a tree.

The two lowest probabilities are summed to form a new probability. Combining of probabilities continues along the branches of the tree until the last two numbers add up to 1.0, which forms the tree root. Each probability is a leaf, and each branch of the tree is assigned a zero or a one. Code words are formed by moving along the branches from the root to the top of the tree, aggregating the binary digits along the way.

If letters are to be encoded, an *E*, which might have a probability of 0.13, could be represented by the code *101*. The three-digit code is constructed by moving from the root along three branches—marking a *1*, *0* and *1*, respectively—to reach the leaf that corresponds to 0.13. The *E* receives a shorter code than a *Q*, a letter that occurs less frequently. By systematically employing codes of varying length, Huffman's idea may reduce by a half or even more the number of code symbols that would be needed if the codes were of a fixed length.

Huffman did not invent the idea of a coding tree. His insight was that by assigning the probabilities of the longest codes first and then proceeding along the branches of the tree toward the root, he could arrive at an optimal solution every time. Fano and Shannon had tried to work the problem in the opposite direction, from the root to the leaves, a less efficient solution. When presented with his student's discovery, Huffman recalls, Fano exclaimed in his thick Italian accent: "Is that all there is to it!"

Products that use Huffman code might fill a consumer electronics store. A recent entry on the shop shelf is VCR Plus+, a device that automatically programs a VCR and is making its inventors wealthy. (Some newspapers on their own list a toll-free number that readers can call for information about where to buy the device.) Instead of confronting the frustrating process of programming a VCR, the user simply types into the small handheld device a numerical code that is printed in the television listings. When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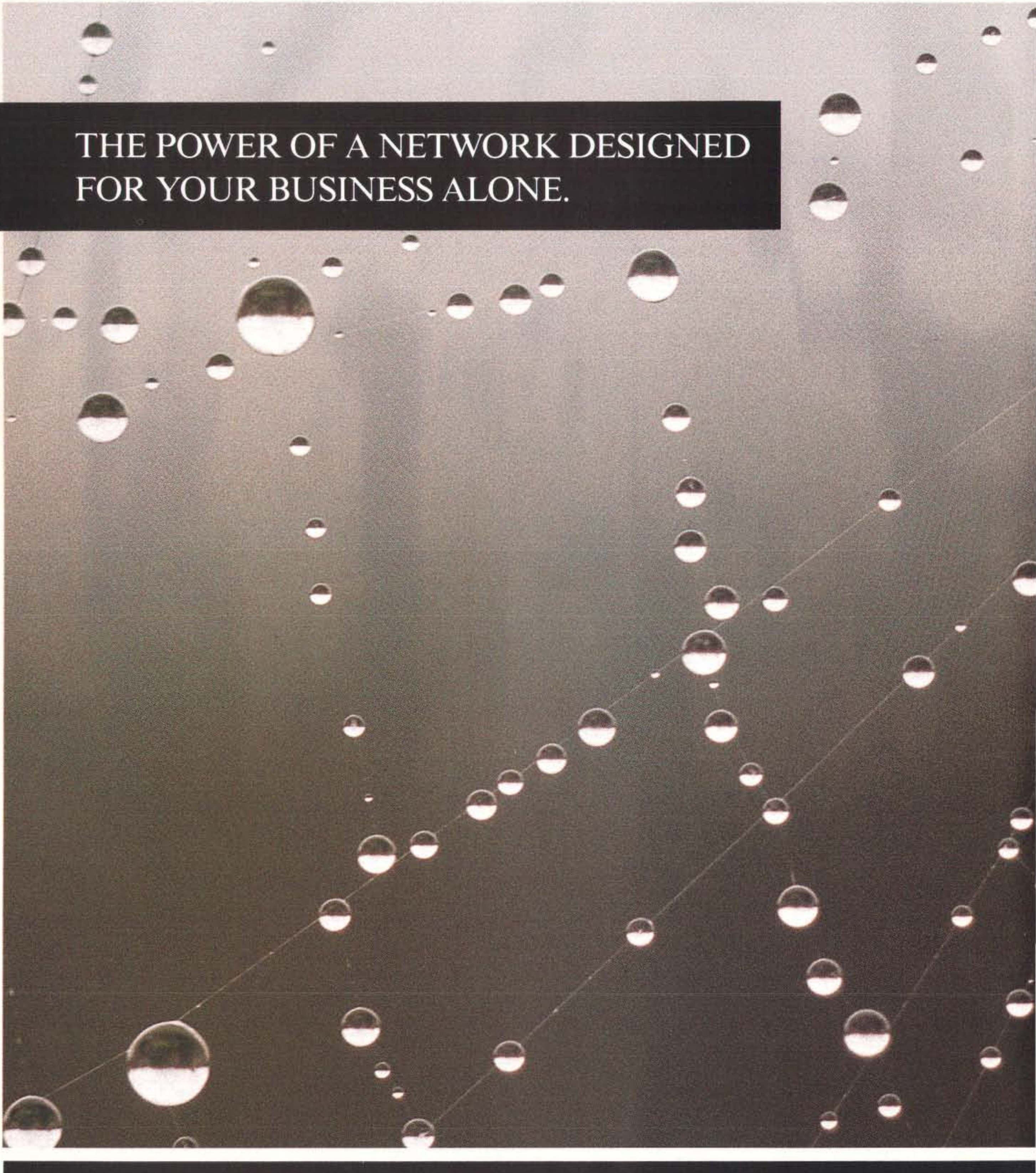

THE POWER OF A NETWORK DESIGNED FOR YOUR BUSINESS ALONE.

it is time to record, the gadget beams its decoded instructions to the VCR and cable box with an infrared beam like those on standard remote-control devices. This turns on the VCR, sets it (and the cable box) to the proper channel and records for the designated time.

Although he acknowledges that he is best known for his code, Huffman says he is most proud of his doctoral thesis, which may be the first formal methodology for devising asynchronous sequential switching circuits, an important type of computer logic. The thesis helped him obtain a faculty position at M.I.T. to teach a course on switching circuits.

His work also attracted the attention of others. During the early 1960s, William O. Baker, then vice president of research for AT&T Bell Laboratories, tapped Huffman to sit on a committee that was reviewing future technology plans for the National Security Agency. What may have attracted Baker was work by Huffman that had outlined a method for converting one sequence of binary numbers into another without losing any information in the translation, a technique that had obvious application in cryptography.

In 1967 Huffman left his position as full professor at M.I.T. to move to the University of California at Santa Cruz, which had lured him to become the first head of its new department of computer science. The relocation brought him closer to the western mountains where he loves to backpack and camp. (At the age of 65, he now prefers snorkeling and body surfing.) Today Huffman is no longer head of the department, but he still teaches a course in digital signal processing at the university.

Huffman's earliest years did not mark him as a prodigy. His mother once told him that he lagged behind other children by two years in learning how to speak. He attributes his slow development to a number of family incidents that led to his parents' divorce and that he has ever since tried to forget. His mother, whom he recalls with great affection, tried to help by becoming a mathematics teacher at a school for troubled children so he could be enrolled there. But a series of tests immediately made clear to his mother and teachers that his reticence had masked precociousness.

At school, Huffman soon leapfrogged his classmates. He finished a bachelor's degree in electrical engineering at Ohio State University at the age of 18 and immediately became an officer in the U.S. Navy, where he served on a destroyer that helped to clear mines in Japanese and Chinese waters after World War II.

Huffman believes his tumultuous early years fostered a love of mathematics. "I like things neat," he says. "I like to wrap things up and get definitive answers, possibly because of the uncertainties of my early life." A sense of order is something toward which he continues to strive. Huffman told this caller that he could spare only 20 minutes. When the time elapsed, an alarm dutifully sounded in the background.

The imposition of structure where none exists has proved a recurrent theme of his career. In the early 1970s Huffman became a debunker of optical illusions. What inspired him were the seemingly incongruous shapes in the work of M. C. Escher: triangles containing three right angles, for example. Inspecting Escher's creations, which he much admires, led him to devise a set of rules to determine whether an artist's picture or a video image had cheated in depicting a two-dimensional representation of a three-dimensional scene.

Huffman determined a method for showing whether the many boundaries between geometric elements in an image—represented as Y, V or T shapes, among others—logically fit into a coherent pattern. He describes his proof as an image grammar. "I wanted to create a sieve so grammatical pictures would go through and ungrammatical images would be seen as unrealizable," he says. This contribution to the young field of scene analysis, which has been used in developing machine vision systems for robots, was presented in a 1971 paper entitled "Impossible Objects as Nonsense Sentences."

Huffman's other work has ranged from the design of radar waveforms to his last paper, published in the early 1980s, which proved that a digital computer could be designed that would virtually eliminate one of the staples of Boolean algebra. Huffman showed that a hypothetical machine could function using only one NOT operation.

"If I had the best of both worlds, I would have had recognition as a scientist, and I would have gotten monetary rewards."

This logic element from Boolean algebra takes a zero or a one and converts it to its binary opposite (NOT zero but one). Huffman called a lecture he gave on the subject, "How to Say No Once and Really Mean It." Says Huffman: "It was totally impractical, but it was a kind of a mind exercise that showed how it could be done. I enjoy pushing things to their theoretical limits."

Since that time, Huffman has exchanged paper writing for paper folding. He wanted to see how the lines and intersections on the flat surfaces that he had pored over in his work on scene analysis could be folded into three-dimensional structures. Using a stylus to emboss lines into paper or thin vinyl sheets, he has concocted spirals, domes and other shapes. Huffman has lectured on the theory and practice of paper folding at M.I.T. and Stanford, among other institutions.

Paper folding goes along with a number of other whimsical pursuits. Huffman learned how to ride a unicycle from Claude Shannon and still keeps one in his garage. His living room, which is adorned with his contorted paper creations, is also sometimes graced with a large red circus ball and his invention of a Bongo Board that rolls in two axes. On Huffman's board, a rider stands atop a bowling ball rather than the standard cylindrical roller.

Although others have used Huffman code to help make millions of dollars, Huffman's main compensation was dispensation from a final exam. He never tried to patent an invention from his work and experiences only a twinge of regret at not having used his creation to make himself rich. "If I had the best of both worlds, I would have had recognition as a scientist, and I would have gotten monetary rewards," he says. "I guess I got one and not the other."

If Huffman were just starting his career, patent attorneys would surely be knocking on his door. Patenting of algorithms is still subject to endless judicial debate. But a lawyer today would tell Huffman to "clothe" his code in silicon, that is, produce a patentable microchip that contains his code programmed into memory. "I bet I could write an application that would be considered patentable," says Richard H. Stern, a patent attorney who was chief of the intellectual property section of the U.S. Department of Justice from 1970 to 1978.

But Huffman has received other compensation. Textbooks on data communications and other digital arts include sections on Huffman code. Huffman has received several awards from the Institute of Electrical and Electronics Engineers. And a few years ago an acquaintance told him that he had noticed that a reference to the code was spelled with a lowercase "H." Remarked his friend to Huffman, "David, I guess your name has finally entered the language." —*Gary Stix*

How nuclear energy benefits a typical family of four.

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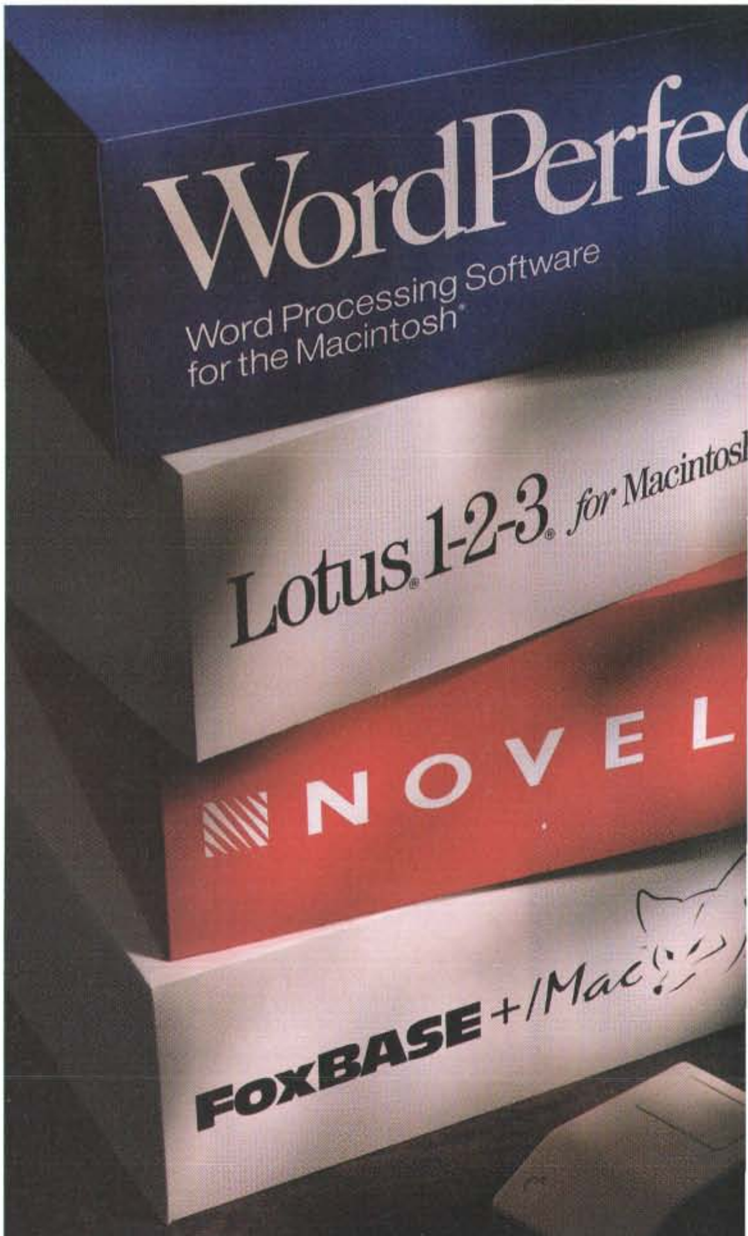

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SCIENTIFIC AMERICAN

Communications, Computers and Networks

By fusing computing and communications technologies, we can create an infrastructure that will profoundly reshape our economy and society

by Michael L. Dertouzos

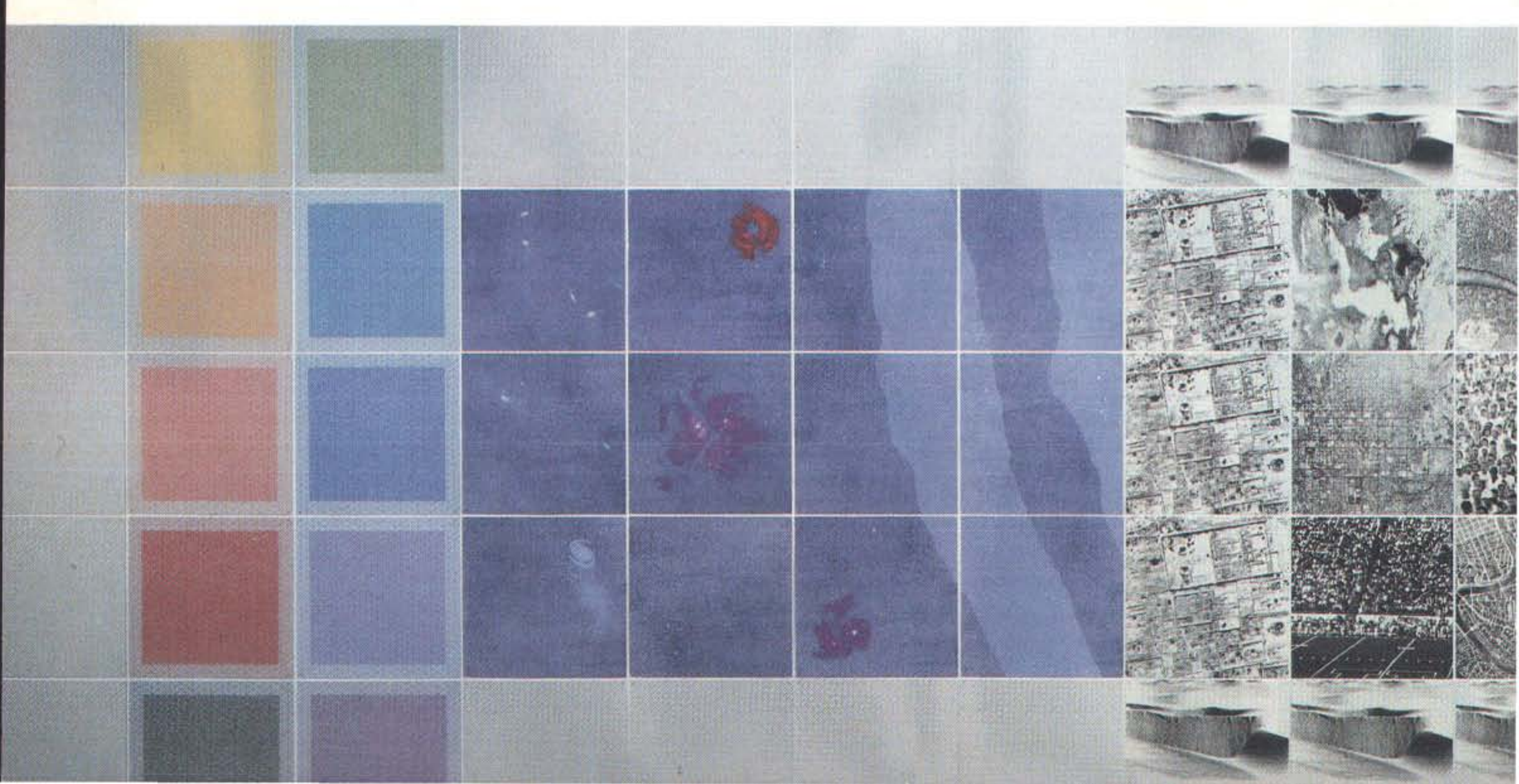
The agricultural age was based on plows and the animals that pulled them; the industrial age, on engines and the fuels that fed them. The information age we are now creating will be based on computers and the networks that interconnect them.

The authors of this issue share a hopeful vision of a future built on an information infrastructure that will enrich our lives by relieving us of mundane tasks, by improving the ways we live, learn and work and by unlocking new personal and social freedoms.

Since the timid debut of the first useful computers almost half a century ago, there has been no shortage of opinion, speculation and prediction about the magical new world they promise. Why, then, devote this entire special issue to this topic at this time? What is new?

A growing opportunity has attained critical mass as a result of a twofold serendipity: dramatic improvements in

"WINDOWS," an eight-by-30-foot mural made of enameled steel by Anna Campbell Bliss, explores the worlds being opened by the innovative use of computers. The artist attempts to span time and place, showing how computers let us see phenomena from the microscopic to the macroscopic. The palette of colors (*left*) is typical of graphics programs. Representations



the cost-performance ratios of computers and of communications technologies. Independent of each other, computing and communicating tools have been improving at the annual rate of some 25 percent for at least the past two decades. This relentless compounding of capabilities has transformed a faint promise of synergy into an immense and real potential.

Computers have grown so powerful and cost-effective that they can be found nearly everywhere doing nearly everything: Supercomputers, manipulating billions of commands per second, forecast the weather and analyze complex medical images. Sensory computers respond to spoken sentences and visually recognize parts on assembly lines. Robotic computers turn those parts into full products. Like the telescope and microscope, computers are opening up new realms for scientists by simulating everything from astronomical collisions to molecular reactions. Fifty million personal computers along with thousands of varieties of software packages help people at work and at home. And millions of computers disappear every year into the cars, microwave ovens, telephones and television sets that they control.

At the same time, the reach and speed of networks have increased by equally awesome strides: millions of miles of glass fibers handle most long-haul communications and are capable of relaying data at speeds of up to a billion bits (gigabits) per second. Local-area networks have become indispensable webs, wiring numerous buildings and neighborhoods. Cellular and other wireless networks reach people while they are driving or even walking. And now these two giants, computers and networks, can be fused to form an infrastructure even more promising than the individual technologies.

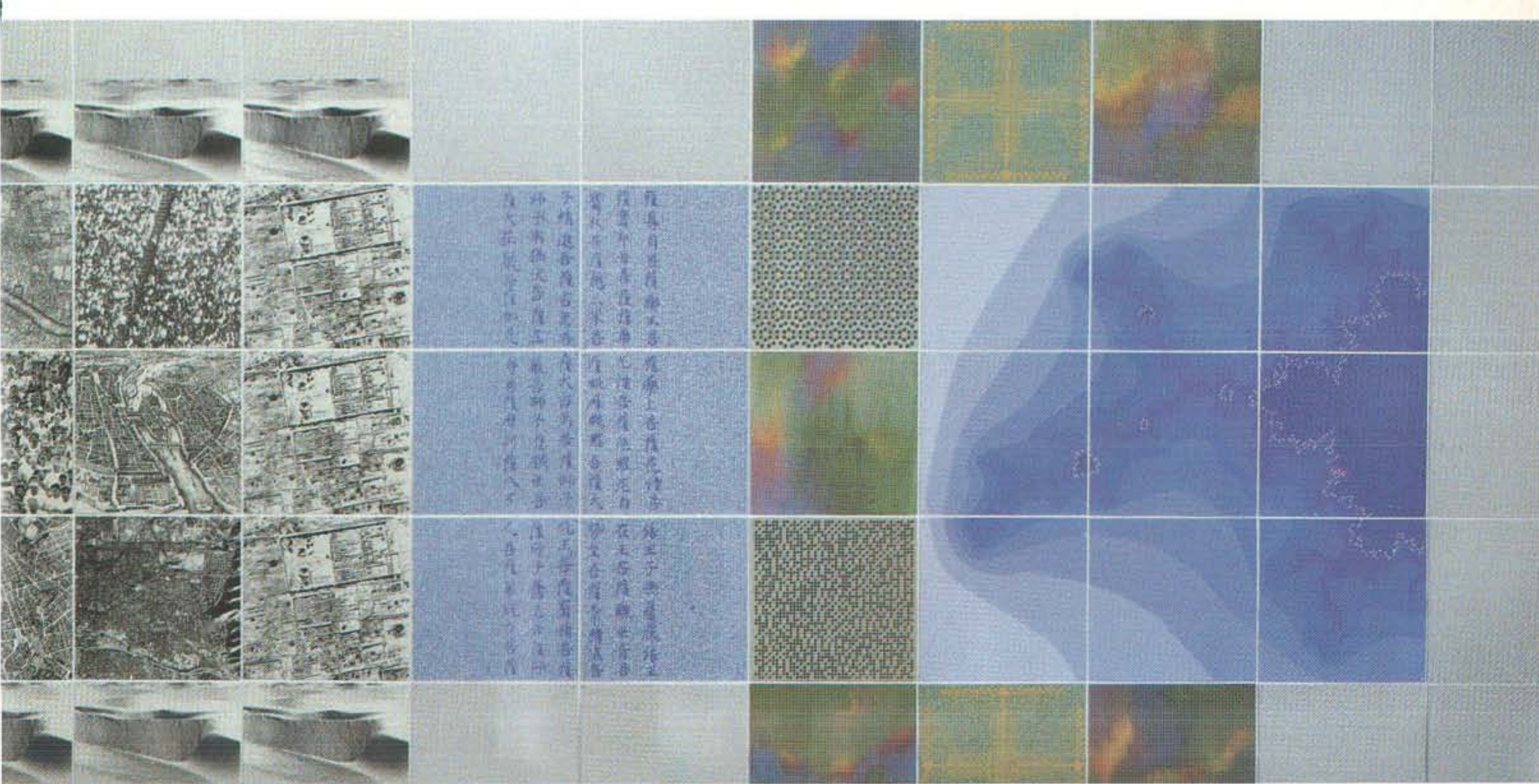
During the past 10 years, we have, moreover, learned lessons about the many useful possibilities offered by the information infrastructure and the difficulties in building it. For instance, throwing computers and networks together without careful development of common conventions that enable them to communicate easily does not lead far.

As we lay the bricks of the information age, trying to envision the ultimate edifice and its uses is as challenging for us as it would have been for writers in the late 1700s to anticipate the automobile, the helicopter, the jet airplane and the myriad of other modern engines along with all that we do with these machines. So we simply offer readers our best impressionistic glimpses into this future, its underlying technologies and surrounding issues.

In a world in which hundreds of millions of computers, servants to their users, easily plug into a global information infrastructure, business mail would routinely reach its destination in five seconds instead of five days, dramatically altering the substance of business communications. A company's designers and marketers would actively collaborate on a product, even when located a continent apart and unable to meet at the same time. Consumers would broadcast their needs to suppliers, creating a kind of reverse advertising. Many goods would be ordered and paid for electronically. A parent could deliver work to a physically distant employer while taking care of children at home. A retired engineer in Florida could teach algebra to high school students in New York City. And from a comfortable position in your easy chair, you could enjoy a drive through your next vacation spot, a trip through the Louvre or a high-definition

MICHAEL L. DERTOUZOS directs the Laboratory for Computer Science at the Massachusetts Institute of Technology, where he is professor of computer science and electrical engineering. He is a member of the National Academy of Arts and Sciences in Greece and a member of the U.S. National Academy of Engineering. He recently chaired the M.I.T. Commission on Industrial Productivity. He received his Ph.D. from M.I.T. in 1964 and joined the faculty at that time. He enjoys playing with computers and sophisticated electronic gadgets, along with dreaming up new interactions between technology and people.

of outer space are juxtaposed with images from pre-Columbian Peru as well as present-day Salt Lake City. Bliss contrasts Chinese calligraphy with randomly generated alphanumeric printing, followed by an interpretation of computer memory. A "fractalscape" evokes the future. The work is on display at the Data Center located at the Utah State Capitol.



movie rented electronically, chosen from the millions available.

Yet the information age has its shadows as well. Will these new technologies widen the gap between rich and poor? I suspect so. Will they cause us to be inundated with "infojunk," mountains of information irrelevant to us? Yes, but we can also use the technologies to shield us from such perils. Will they threaten to dehumanize people? I doubt it. But will these technologies also increase white-collar crimes and violations of privacy? We don't know; we must be vigilant.

And as has been the case for much technological change, the glorious possibilities we describe in this issue stem more from opportunism than they do from pressing human need. Consequently, we, the designers and users of this information infrastructure, bear a serious responsibility: we must understand the value and role of information so that we may better channel our technological miracles into useful rather than frivolous, if not dangerous, directions.

VOYAGER, an interactive speech-recognition system that provides a street guide to Cambridge, Mass., is being developed at the Massachusetts Institute of Technology.

Information touches all human activity. It comes in a multitude of different shapes—speech, pictures, video, office work, software, great art and kitsch, invoices, music, stock prices, tax returns, orders to attack, love letters, novels and the news. We have also created many ways of conveying information, from cheap, large newsprint pages to postal systems to telephone, radio and television networks. Virtually all these schemes require humans at the receiving end to understand and then to act on the incoming information.

Similarly, computers and networks are bound together by information and can fulfill roles roughly analogous to those of people and their communications schemes. Computers accept, store, process and present information; the networks move information among the machines they interconnect. Computers can manipulate information far faster than people ever will. But unlike people, machines almost never understand the messages they are manipulating. To them, information is only a deceptively uniform sequence of numbers—ones and zeros.

One key idea behind the information infrastructure is to relieve people of a good deal of the work of communicating and processing information. To do so, the machines must intelligently handle some of the dazzling diversity of concepts that information represents. They must therefore begin to understand, even at a crude level, what the ones and zeros mean. In contrast, the current state of affairs is tantamount to a community of telephone callers trying to work with one another using only meaningless grunts of different loudnesses to convey messages.

Understanding the value of information, though, is difficult even for people. Although we are continually besieged by information, we have at best only an intuitive grasp of its meaning and almost no sense of how to value it. How valuable is a 300-page report on a company's stock? What makes a 15-page booklet or a well-placed stock tip more valuable?

Until a better explanation is devised, let me suggest that information has economic value to people only if it can lead them to the acquisition of tangible goods. Similarly, information has intangible value if it can enable them to satisfy less tangible human desires. An encyclopedia publisher, for instance, will find a mailing list of prospective buyers useful because it might increase sales. Watching a soap opera has value for those people who want to experience heartrending emotions.

Because information leads to goods only indirectly, it seems reasonable to value it as a fraction of the worth of the tangible goods to which it leads. If information leads to goods through intermediate pieces of information, each one derived from the others through processing, then all the intermediate data and programs should also be somehow valued backward from the end results.

Using these ideas, we can measure the economic value of all that will transpire on tomorrow's sprawling computer-and-network complexes as a fraction of the tangible goods to which they will lead. Today an industrially advanced and wealthy country such as the U.S. places the value of its computer hardware and software, including the work needed to run computer systems within organizations, at almost a tenth of its gross national product—roughly about \$500 billion. Yet because some 60 percent of the work force have jobs that involve information, the value of computerized information handling may well grow to an even larger fraction of the U.S. economy.

Valuing information this way points out some sobering lessons to bear in mind as we embark on the information age. To be valuable to us, tomorrow's computers and networks must help us achieve our tangible goals even as they shield us from the barrage of infojunk produced by others aiming to achieve their own goals. This objective raises to a still higher premium the need for computers and networks to understand enough content so they can isolate, simplify and present useful information and reject irrelevant data before they clutter users' lives.

Thinking about the value of information brings home another lesson: that information and its processing have less value in poor countries because there are not many tangible goods to which they can lead. Yet there are other ways in which information can play an important role in these countries. It can help teach people to take better care of their health, to fix machinery or to establish better farming practices. Information might also improve the distribution of food and medicine. Countries with well-educated pools of labor, such as India, may even earn foreign exchange by writing software for overseas consumption.

On balance, however, information more naturally boosts the wealth of those who already have material goods—simply because those communities already have so many tangible goods to which information can lead. Unless wealthy countries see it as their

duty to help developing nations make good use of the evolving technologies, the information age will likely widen the rift between the haves and have-nots.

Rich nations must also remember that if they become enamoured of and blinded by the glamour of the information era and neglect to produce and improve tangible wealth—such as food, manufactured goods, natural resources and human services—the information colossus will lead to nothing and so will collapse. Information is, after all, secondary to people's principal needs—food, shelter, health and human relationships. In a crisis, even the most dedicated hackers would trade millions of bytes of software for a few bites of bread.

We begin to reap the value of information when we have created an infrastructure that leverages our work. The existing web of computer, telephone, broadcast and other kinds of networks does not constitute the kind of powerful information infrastructure that we envision—no more than the thousands of U.S. dirt roads in the early 1900s made a national highway system. Intrepid travelers could drive from one place to another by navigating over those twisting passages, but such trips were slow and difficult.

Well-established infrastructures, such as the present highway system, the telephone network and the electric power grid, have several simple but powerful properties. They are widely available: accessible to practically every American is a well-paved road, at least one telephone and several electric power outlets. These infrastructures are also easy to use. No more effort is required than pushing a plug into an electric socket or talking into a telephone. And most important, these infrastructures serve as the foundations for countless useful activities. We conduct business deals and family chats over the telephone, ferry people, food and every conceivable good over the highways, and so on.

Using these yardsticks, we can see that no information infrastructure exists anywhere in the world today. Learning how to use a computer still causes headaches. And it is impossible to build even one application that can be used by all the nation's computers.

To escape the present chaos and to fashion our computers and networks into a true information infrastructure, we must endow networks with three key capabilities: flexible information transport capabilities, common services and common communications conventions.

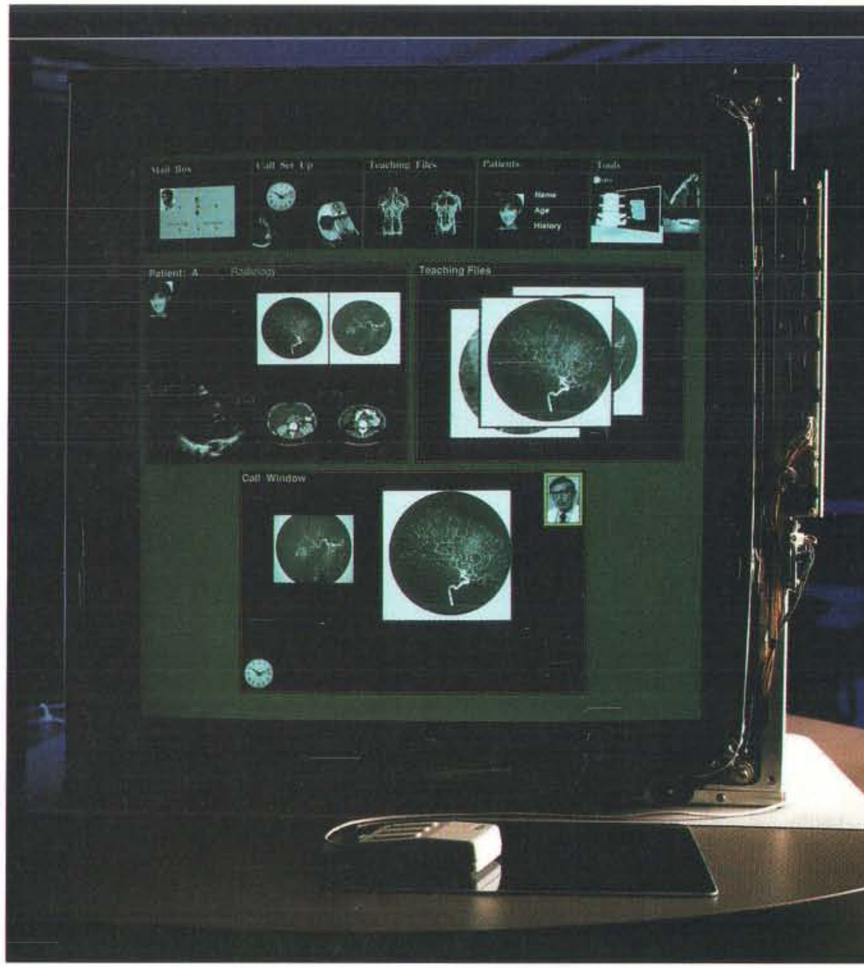
Flexible transport means that the infrastructure can carry information among computers with various degrees of speed, security and reliability. This requirement is vastly different from the capabilities of the telephone infrastructure, which was built to carry digital voice signals at a fixed speed of 64,000 bits per second with uniform degrees of security and reliability.

Humans only talk on telephone networks; computers carry on far more diverse activities. Computers can convey information at a wide range of speeds, from a few thousand bits per second for sending a brief text message to tens of millions of bits (megabits) per second for shipping high-resolution video.

Depending on their tasks, computers also have variable access and security needs: arranging a personal loan electronically demands more security than does chatting openly on an electronic bulletin board about the Boston Celtics. Some messages must also be sent with more precision than others. Conveying software, funds or lifesaving medical data requires perfection. A certain laxness, on the other hand, is tolerated in the transmission of photographs, in which case a few lost bits do not alter the meaning of the message.

If users or their computers can set these "levers," that is, choose the combination of transmission speed, security and reliability appropriate for their task, then they need only pay for the service they want. The alternative—a highly secure and lightning-fast transport service that would satisfy all potential needs—would be so expensive that it would never become widely used.

As Vinton G. Cerf points out, the U.S. is making gradual progress in building the hardware for a flexible network [see "Networks," page 72]. Telephone companies and other network builders continue to lay down optical fiber lines that are capable of transmitting thousands of times—or eventually hundreds of thousands of times—more traffic than the traditional copper wire. An emerging standard for future telephone service, called broadband integrated-services digital network, will let users transmit data at speeds of up to 150 megabits per second. By the end of the



PROTOTYPE MULTIMEDIA MEDICAL TOOL, developed by NYNEX and displayed on a high-resolution screen, shows the kind of information that physicians at four Boston hospitals can reach via an experimental network.

1990s, the U.S. may have in place a working gigabit network, capable of conveying video images that will rival prize-winning photographs in their vibrancy and crispness.

Flexible service also means that people can tap into the infrastructure wherever and whenever they want. Wireless networks based on cellular and satellite systems will make this access possible by letting automobiles and people walking on the street be part of the world's information infrastructure.

The second component of a proper information infrastructure is a set of common services that would be available to everyone. At a minimum, there must be a few basic and necessary common resources, such as directories—electronic white and yellow pages—of users and services. But there could be richer, universally shared resources as well: government tax codes and regulations, census data, the paintings in the National Gallery and the 15 million books in the Library of Congress.

To understand the third and most important ingredient of an information infrastructure—common communications conventions—consider again the frustrations of people trying to communicate with grunts over the telephone. Any pair trying to communicate may assign meanings to a few specific grunts so they can understand each other. Crude as it may sound, that method is used today within groups of interconnected computers. A company and its suppliers, or even people within one large firm, draw up agreements to establish specific formats for exchanging information. Although this approach works well for a small number, it becomes absurd for a larger community. It is far more economical for everyone to agree on some conventions—in other words, on a common language.

PAPERLESS FACTORY at Raychem-Advanter in Richmond, British Columbia, relies on computers at every step in the manufacture of very small batches of aluminum adapters in thousands of sizes. A technician, who receives on-line information about the next job, uses an optical system to measure the new cutting specifications and so can reset the lathe in just 12 minutes (*top*). As the computerized numeric-control lathe begins cutting the part (*bottom*), a technician can also monitor the work using a continual stream of quality-control data.

One way to create such a language for computers involves what I like to call E-forms, or electronic forms. E-forms, the computer equivalent of mail-order forms, would be instantly recognized by any computer on the network that needs to do so. A handful are already in use. Several years ago corporations agreed on a broad format called the electronic data interchange (EDI) for settling business transactions, including sending invoices and ordering parts. Electronic services, such as Prodigy (developed by Sears, Roebuck and Co. and IBM), CompuServe and Dow Jones News/Retrieval, offer E-forms for ordering airplane tickets and some merchandise. Unfortunately, these early E-forms are not universally used by computers but are restricted to those clients who pay for the services.

Eventually E-forms might be filled in by speaking rather than by typing. A few prototypes exist: bond traders at Shearson Lehman Brothers and about 40 other firms use voice-activated assistants to record sales of government securities. The machines have small vocabularies, however, and must be trained to understand a specific broker. A research system at the Massachusetts Institute of Technology, called the Air Travel Information System (ATIS), helps people wishing to book flights. It understands continuous speech by any speaker—including those who have accents—provided the person wants to order a ticket. People normally phrase questions in many different ways. Yet the computer need only fit the question asked into one of a few categories. As a result, voice E-forms are much more feasible than general-purpose systems for understanding speech.

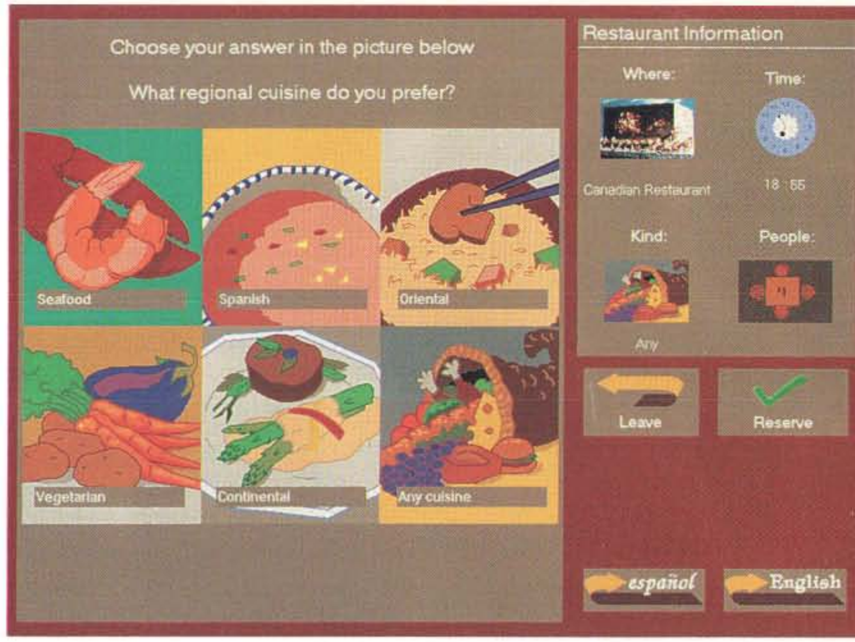
Whether typed or spoken, E-forms can also bridge different languages. For instance, an American ordering a pair of Italian shoes need only fill in an E-form in English; it would then automatically be translated into the corresponding E-form in Italian. Such facile translation may make E-forms a key factor in the European Community's quest for commercial unification, providing the participating countries with an easy means to overcome linguistic barriers in routine business transactions.

An alternative to this E-form Esperanto would be a Knowbot, first developed by Cerf and Robert E. Kahn at the Corporation for National Research Initiatives (CNRI). Knowbots are programs designed by their users to travel through a network, inspecting and understanding similar kinds of information, regardless of the language or form in which they are expressed.

Suppose, for example, that you wanted to create a list of all the available car models that have enough backseat leg room for tall people and cost less than $18,000. If details on various vehicles are available through the information infrastructure but are represented in different formats by the manufacturers, you might unleash a Knowbot to roam the net and scan the various forms. Your Knowbot would understand enough about the different ways the same kind of information may be represented to glean the relevant details from every entry. It would then process and present the information to you in a useful and familiar way. An early prototype Knowbot, designed by the CNRI, combs through data bases developed by the National Library of Medicine for salient facts on people in publicly available data bases.

Because Knowbots can be tailored to meet a person's needs and can tolerate diverse representations of information, they look more desirable than E-forms. But as we ask these programs to act with greater intelligence, they become far more challenging to build.

Beyond creating a proper infrastructure with these three elements, we must also develop computer hardware and software that can more naturally connect people and machines to the information infrastructure and, as a result, to one another. Lawrence G. Tesler discusses how designers are trying to transform hardware into tools as accommodating as a wristwatch [see "Networked Computing in the 1990s," page 86]. Most important, we must rethink how to link people and machines at the cognitive level so as to communicate understanding instead of grunts. To this end, Mark Weiser proposes we find ways to make the hardware fade into an inconspicuous feature of the environment, even as it enhances our understanding of the events and people around us [see "The Computer for the 21st Century," page 94].



ON-LINE RESTAURANT RESERVATIONS can be made through a computerized guide (developed by IBM) to the 1992 Universal Exposition in Spain. Users pick a cuisine. Networked computers then relay the relevant restaurants and menus; they also take reservations. In addition, the system provides an electronic bulletin board.

The most vibrant infrastructure we can build is one that allows free enterprise to flourish. The telephone companies will play a major role in laying down the physical fibers for the network and so bear the responsibility for providing flexible information transport services, some minimal common services and access to major shared resources. But neither the telephone companies nor any other centralized body should decide what common communications conventions should be offered; that should instead be the role of special-interest groups working outside the purview of the carriers. In addition, no central agency should have anything to say about what services will be offered through the information infrastructure. These new products and services should be devised by the millions of people and their computers that will use the infrastructure according to their own plans and for their own purposes.

The information infrastructure will then resemble an old-fashioned village market. A multitude of goods and services will be bought and sold through this new information marketplace, as I like to call it. As in traditional markets, not all transactions will be monetary. Some people will publish free manuscripts, others will engage in debates and still others will collaborate in creative and entrepreneurial ways, all through the network.

We can begin to imagine the information marketplace by thinking about how it will change familiar information-handling services such as today's business mail. There is no reason to treat much of the mail as precious physical goods. The message is usually more important than the paper on which it is printed. This does not mean we are obliged to send a video clip of shimmering red roses to someone we love. But when the content is more important than the medium, it is wasteful to transport the paper conveying the message.

A speedy and flexible nationwide electronic mail service could dramatically enhance the competitiveness of domestic industries. Whether a nation becomes a major producer of manufactured goods and services depends heavily on the quality and cost of the products it generates and the speed with which the products reach the market. Lowering the cost of production and trimming the time needed to design, produce, sell and service products are all intimately related to the speed and flexibility of communicating and processing business information.

In addition to conventional advertising, manufacturers' computers may respond directly to queries for products with special features and prices broadcast by the computers of potential consumers. Before buying a car, for example, a consumer would interact with the manufacturer's computers: via the infrastructure, she might request certain basic features (namely, four-wheel drive), scrutinize the models that fit, then further tailor the car to her needs and wishes by selecting specific options, fabrics and colors.

Once the sale is made, her order would touch off an explosion of computer network activity. Automatical-

ly, her descriptions would expand into a cascade of orders for the necessary systems and subsystems of the car. The order would then generate instructions that would time the arrival of these parts to the production floor and would direct the floor to assemble all these pieces. Such services could lead to the mass production of individualized products. As Thomas W. Malone and John F. Rockart point out, networks may enable independent contractors to create an organization overnight to fill a customer's specific demand—and then to dissolve it just as quickly [see "Computers, Networks and the Corporation," page 128].

The information marketplace will also change how we work with geographically distant partners. An increasing number of conferences are already conducted over video links, but these conferences still require all the participants to be in the right place at the right time. New approaches to such collaborations will free people to take part in delayed and distributed meetings. Lee Sproull and Sara Kiesler address the social and managerial implications of such "virtual" collaboration [see "Computers, Networks and Work," page 116].

CUSTOM-TAILORED TEXTBOOKS may help teachers design lessons that meet the specific needs of students. One such effort is McGraw-Hill's Primis software shown here.

Other services and opportunities also become possible as the infrastructure dissolves geographic and temporal barriers. Remote medical diagnosis and perhaps, some day, remote manipulation would bring experts close to needy patients who are physically thousands of miles away. The long-promised links between the workplace and the home would finally be forged. Besides offering many people the convenience of working at home, the network would also open up new career opportunities for housebound parents of children and for physically handicapped people.

Because the infrastructure so rapidly handles the transport and processing of information, the services likely to gain the most efficiency from the infrastructure are those that involve only information. Securing advice on a specific legal, financial or medical problem could become a relatively easy and low-cost undertaking. Prospective vacationers could explore a virtual island retreat from their home before booking tickets. Inquiries about government regulations would be answered in minutes rather than in months. Advice on building a house or baking a chocolate soufflé would be at hand at any time.

Computers are already heavily used in military training; specially designed flight simulators for pilots and sophisticated war games for strategists have become standard practice. As networked computers grow cheaper and more powerful, companies, too, will be able to afford such approaches. A firm might train its managers by confronting them with simulated problem scenarios involving employees' complaints, project bottlenecks or one another. Other companies might sell such simulation services through the information marketplace.

Even though much has been said and written about computers and education, we have yet to find the most effective ways of applying computers to help people learn. As Alan C. Kay points out, computers do not magically improve schools. When used to drill students on rote memorization, the machines add little value [see "Computers, Networks and Education," page 138]. But by enabling students to interact with rich intellectual resources, including distant teachers, libraries and museums, the infrastructure can be a strong ally in general education.

In specific cases, we are discovering approaches that seem effective. At M.I.T., students participating in Project Athena learn French as they engage in a simulation of trying to rent an apartment in Paris. A high-resolution moving image of a French speaker asks questions that students must answer.

Eventually the infrastructure may even couple individualized computer tutors with students. One such tutor might help a student analyze a specific bridge or, at a more ambitious level, design bridges. If we can make research dreams come true, an even more advanced tutor, endowed with the design approach and style of Frank Lloyd Wright, might help a student become a virtual apprentice of the master.

Entertainment and publishing will be greatly enhanced by the information infrastructure. We will have easy access to millions of movies and music performances by renting them from collectors who offer their goods in the information marketplace. Video broadcasters, radio stations and videotape rental stores may lose some of their monopolistic hue as the information marketplace connects every supplier to every consumer throughout the nation and the world.

Printed newspapers are unlikely to disappear because they are so convenient and inexpensive. But the information marketplace will also be an abundant source of timely information—including text, advertisements, music and video—contributed by anyone and perused freely by anyone else. These mountains of information will, in turn, create opportunities for a breed of electronic publishers and entrepreneurs who will sift for diamonds, which they can then edit and publish electronically. Thus, even though publishers may not print their works on paper, the substance of gathering and reporting information will not change. Nicholas P. Negroponte describes related products and services that will emerge [see "Products and Services for Computer Networks," page 106].

Not only will the information marketplace enhance specific sectors of the economy, but even greater collective benefits will flow from binding together previously unlinked parts of the economy. Consider, for example, the likely evolution of high-definition television (HDTV). With the information infrastructure in place, all the vexing questions about how HDTV will develop and who will control it will fade. Instead we need only adjust the flexible transport levers to make HDTV a reality, linking every home and office to every broadcaster and video rental service in the information marketplace. Interactive, how-to instructions, virtual museum visits or simulation sessions could exploit the visual power of HDTV, thereby benefiting the suppliers of and the many services that use high-definition

video as well as the country that has this infrastructure treasure trove.

Where will this information mania lead us? As we think about how far we might use the technologies to stretch the ways people live, learn and work, we anticipate that a sophisticated information infrastructure should help in three ways. It should relieve many of the repetitive, boring and unpleasant tasks related to processing and communicating information. In this case, the computers' effectiveness will be limited only by the extent to which they have been designed to understand the information that reaches them, regardless of whether the information is supplied by people or by computers.

Second, the information infrastructure should help us improve the ways we do things now, by speeding up existing processes or by improving their quality. Although the flow of information can be greatly accelerated, the ultimate limits to these improvements are governed by the physical work involved, including those tasks that only people can carry out. No matter how fast the information flows, assembling a real car out of real parts still takes real time.

The third major way computers and networks will touch our lives is by unlocking as yet unexplored possibilities. The neighborhoods we play in and the people with whom we do business no longer need be the ones close by but the ones we choose.

There is no question, too, that computers and networks will democratize human communications. Nearly everyone would be able to put his or her ideas, concerns and demands before all others. This freedom will undoubtedly bring sociological consequences, including the formation of electronic tribes that can span physical distance.

The manipulation of video, sound and text by computers will let us explore new vistas. It will also further blur the boundary between virtual and real experiences. Even a plain old movie can deeply color the moods of passive viewers. What might tomorrow's interactive, multisensory movies inspire?

Influential as these tools will be, there are obvious limits to how much they will change our lives: no amount of virtual reality can substitute for people's real needs. Neither can computers and networks augment the human capacity to absorb information or the number of people with whom a person can interact or the quality of human relationships.

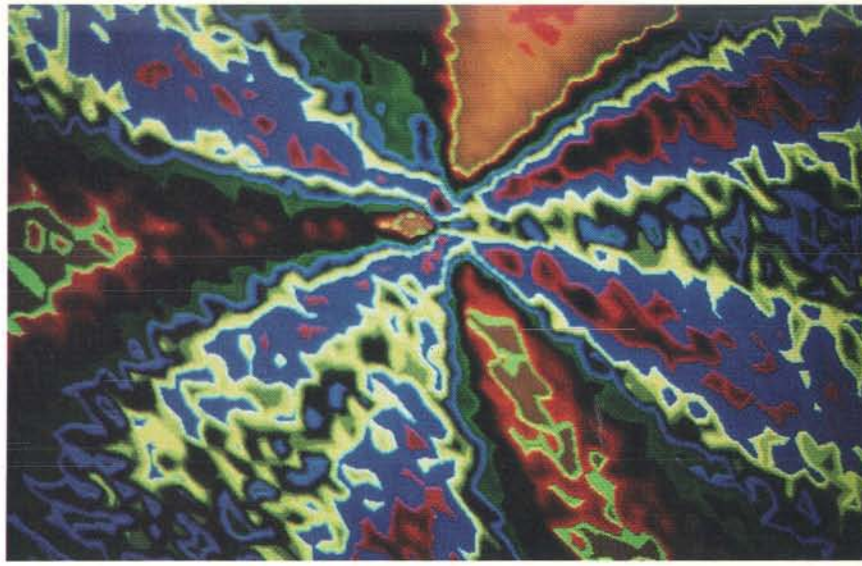
The information infrastructure will also introduce new challenges for society. Who should be liable for computer services that misbehave? I believe the people or companies who profit by providing the services should be accountable. How will we ensure personal privacy on the network and yet protect users from computer crimes, worms and viruses? We cannot yet answer questions like these with much certainty, but we should not hesitate to try to anticipate them, as both Anne W. Branscomb and Mitchell Kapor do [see "Computers, Networks and Public Policy," page 150].

Yet even as some of the promises that we seek will turn out to be mirages, so, too, some of the problems will evaporate like bad dreams. Some people worry that these new technologies will tend to dehumanize us. In the worst technophobic scenario, men and women fixated on computer screens and plugged into networks are rendered spiritless and become trapped in lonely and cruel isolation. I find such concerns implausible. People are neither so naive nor devoid of instincts for self-preservation and control that they will surrender their humanity to their tools.

Information infrastructures will evolve first in those industrialized countries that need and can afford them. Senator Al Gore identifies the role that national governments must take in developing these infrastructures [see "Computers, Networks and Public Policy," page 150]. Like the traditional highway and power systems, these information infrastructures will be woven tightly into the fabric of a nation, hard for others to copy or to emulate. And like these earlier infrastructures, they will give their builders certain unique economic advantages.

Once several national information infrastructures are in place, countries will tie them together, much as national power grids, airline routes and telephone circuits have been linked in the past. The result will be a global information infrastructure that will help the people of the world buy and sell information and information services and share knowledge and creative energy—we hope to the benefit of all.

The opportunities along with the problems that may well arise on tomorrow's computers and networks will be new, different, unpredictable and worthy of our continual vigilance. Harnessing the electronic agents that will emerge from this infrastructure to support humanity may be our ultimate challenge. And yet the opportunities and shadows we face as we try to achieve our goals in the information age are consistent with those we have grappled with during the agricultural and industrial eras. The alternative—closing the door to technological discovery so as to avoid societal pitfalls—is unacceptable to the probing nature of the human spirit.



"STARBURST #21," a computer-generated work by Lillian Schwartz, represents the artist's view that "what the computer can do is subject to what we believe it can do for us." It appears in *The Computer Artist's Handbook*, published by W. W. Norton.

FURTHER READING

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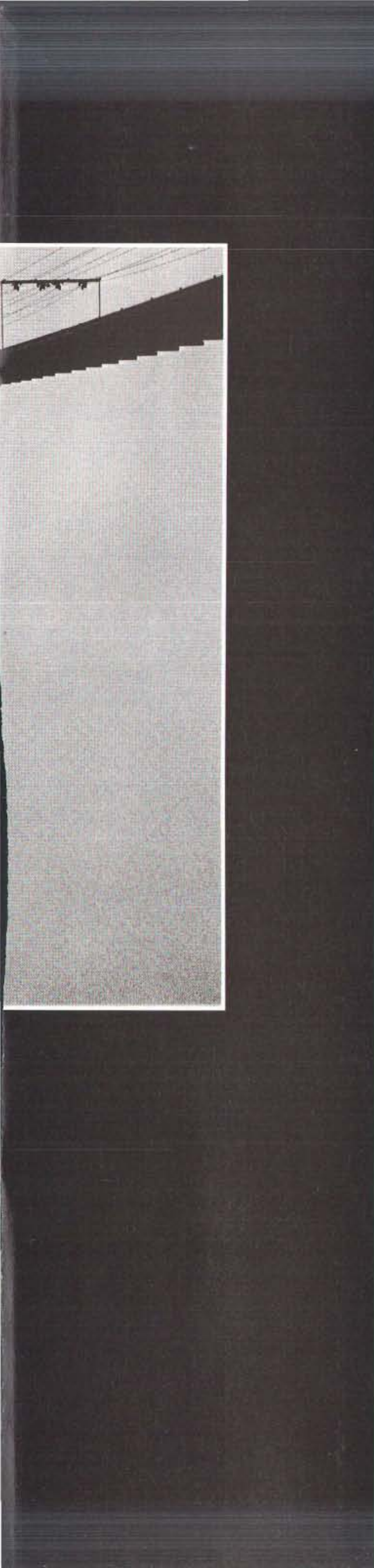
BUILDING THE INFORMATION MARKETPLACE. Michael L. Dertouzos in *Technology Review*, pages 29–40; January 1991.

M.I.T. PROJECT ATHENA: A MODEL FOR DISTRIBUTED CAMPUS COMPUTING. George A. Champine. Digital Press, 1991.

Photograph by Bruce Davidson



Networks

As the diversity of computer applications increases, the burgeoning flow of megabit traffic between machines will be accommodated by wider and smoother highways

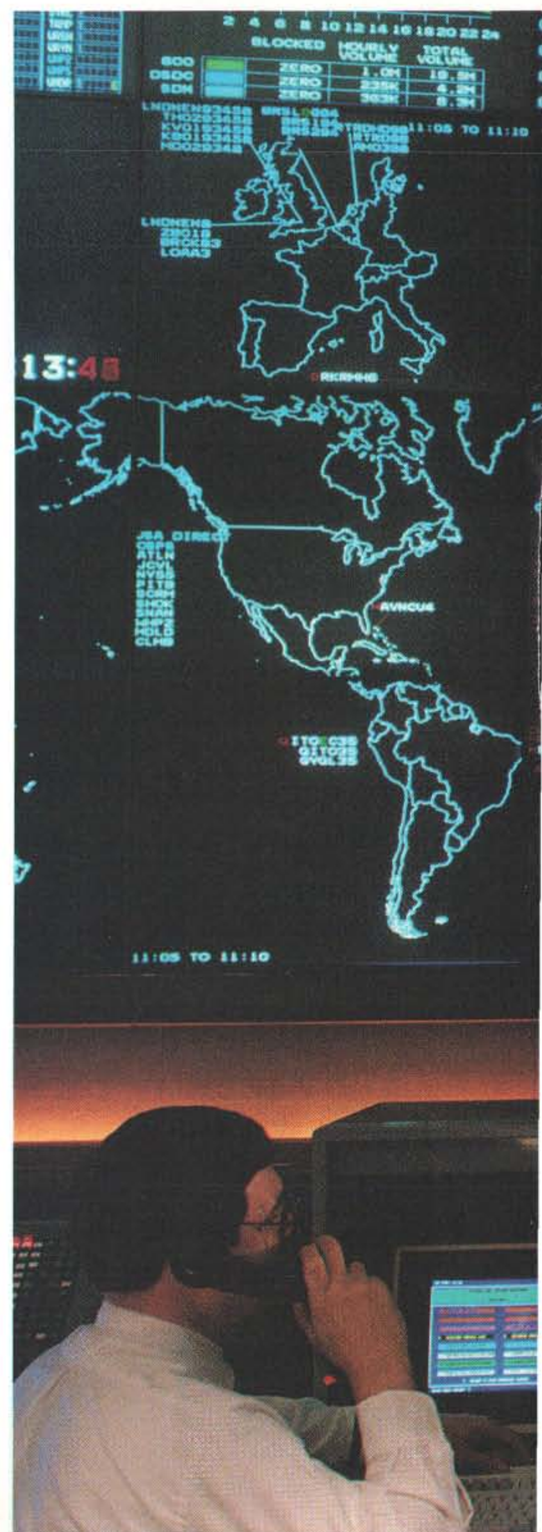
by Vinton G. Cerf

A web of glass spans the globe. Through it, brief sparks of light incessantly fly, linking machines chip to chip and people face to face. Ours is the age of information, in which machines have joined humans in the exchange and creation of knowledge.

As the diversity and sophistication of computational machinery have increased, so have the demands on the networks transporting the information and knowledge generated. Pathways must carry scientific and technological data and also provide links for everything from entertainment to complex computational modeling. Systems must be able to sustain communication rates that range from a few characters per second to billions of characters per second, a span that encompasses keyboard character strokes, high-resolution X-ray diffraction imagery and full-motion supercomputer weather simulations. Moreover, multifunction programs may need to talk to other multifunction programs; for example, a user running a word-processing program, a spreadsheet and a desktop graphics program may want to set up a collaborative link with a colleague running similar programs at a distant site.

What is needed to support the burgeoning flow of megabit traffic? What structures are already in place, and what must be built? How should the existing infrastructure—the set of products, services and functions underlying all aspects of networking—be modified? How can users make appropriate choices about the quality of service (speed, accuracy and security, for example)? And how will the system execute these decisions? Such questions fuel current research and development in computer networking. They are made even more challenging by the communications support that multiple applications may need: one can imagine that an unknown arbitrary number of programs running in an arbitrary number of computers may need to communicate with one another at arbitrary times. To meet these requirements, the networking technology must find a way to facilitate the exchange of information among many different computers concurrently. Indeed, the shift from the need to support simple, remote interactive access to a computer to the more difficult task of supporting machine-to-machine interaction has profoundly influenced the development of computer networking technology.

One prerequisite to any successful form of communication is the choice of



NETWORK CONTROL CENTER in the Philadelphia area from which AT&T monitors the flow of voice, data and entertainment traffic typifies the kind of communications system that will require significant enhancement to support growing computerization. Advances in the use of computers in business and professions, expanding consumer services and new entertainment media create the need for changes. The system must be able to handle many classes of traffic, which range in frequency from hundreds of bits per second to billions per second and which bear varying requirements for accuracy and confidentiality.

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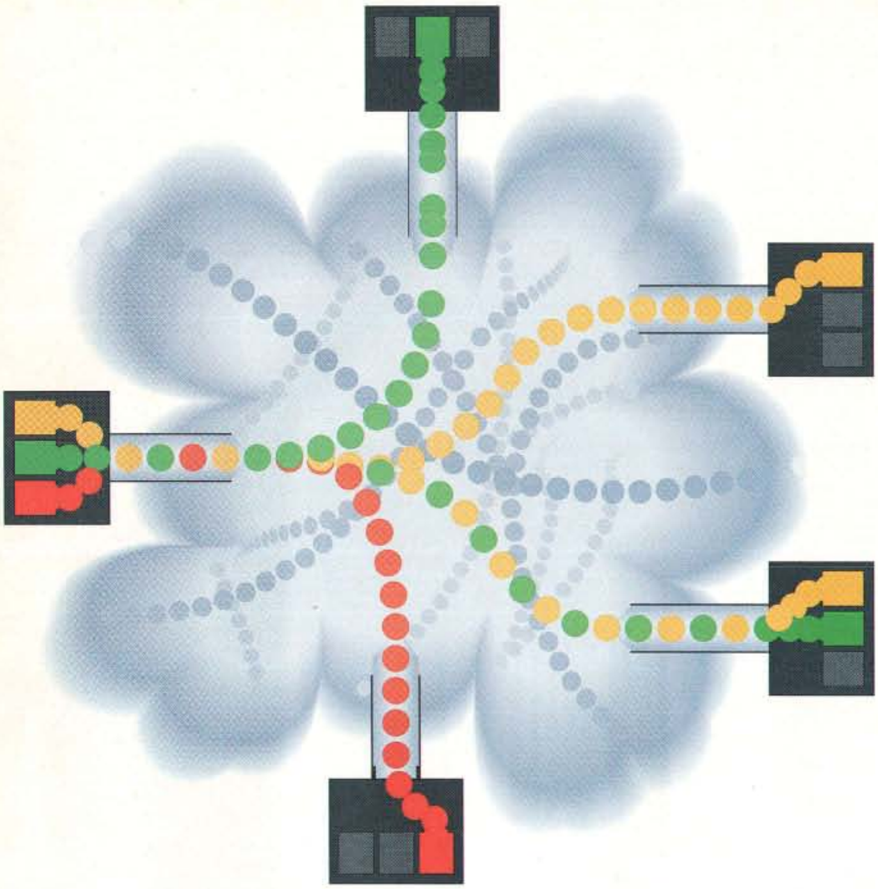
a common language. In computer networking, it is essential that the communicating programs share conventions for representing the information in digital form and procedures for coordinating communication paths. Like their human counterparts, communicating computers must agree on ground rules for interaction. In personal terms, we might agree to use the postal service to exchange postcards and to use English as our common language.

A computer communications protocol consists of a set of conventions that determine how digital information will be exchanged between programs. The conventions can become quite complex, and so they are often organized in a hierarchy with the most basic agreements at the lowest levels and the more sophisticated and special-purpose agreements toward the top.

Once a language and a set of conventions have been chosen, the next question is how to minimize the number of interfaces ("spigots") required to link a computer to the network. The most effective way is multiplexing: each computer feeds information into a single high-capacity link to the network, to which the other computers are in turn connected [*see illustration on next page*]. Information from each computer is labeled so the network can route information to its proper destination. Ideally, a network can deliver information to all (broadcast), to a subset (multicast) or to only one recipient.

Such manifold computer interactions are often referred to as distributed computing. The term covers a multitude of applications and protocols. A



WIDE-AREA NETWORK moves data among computers through high-speed links. (The network is represented as a cloud, which is the term for it used among computer scientists.) Information packets from several programs running on the same computer may be multiplexed together. In addition, the network can deliver the same message simultaneously to several different addresses, a process known as multicasting.

popular distributed computing concept is called the client-server model. In this model, one computer provides a service, which another computer accesses as a client. For example, one or more computers might be dedicated to storing files of information for all the other computers. Various machines in the network can ask the "file servers" to deliver copies of files on demand. Another set of computers might be dedicated to providing laser-printing services. More generally, a number of computers might be dedicated to providing access to vast quantities of catalogued information in on-line data bases.

Autonomous, interprogram communication is being explored today in an even more general form under the rubric of knowledge robots (Knowbot is a registered trademark of the Corporation for National Research Initiatives), programs that move from machine to machine, possibly cloning themselves. Knowbots support parallel computations at different sites. They communicate with one another, with various servers in the network and with users. In the future, much computer communication could consist of the interactions of Knowbots dispatched to do our bidding in a global landscape of networked computing and information resources.

In any kind of multiplex network, there are two means of relaying information: circuit switching and packet switching. Circuit switching, the familiar technique that links telephones to one another, can make sense whenever two computers need to be connected for a long time to transfer large amounts of information. Its speeds typically range from a few hundred bits per second to a few million. Nonswitched dedicated data circuits can operate at speeds of nearly 45 million bits per second, but the expense of such a system must be justified by a nearly continuous need to transmit data between computers.

Circuit-switched systems suffer from a severe drawback: they often do not prove satisfactory for applications requiring that multiple programs running concurrently in one machine communicate with programs running in different machines. In such cases, it would be necessary to reconfigure the switching system from one computer to the others in turn, a process that takes an inordinate amount of time. Compared with the few microseconds (millionths of a second) or less it takes a computer to finish a computation, setting up and tearing down circuits can take hundreds of milliseconds (thousandths of a second) or more—enough time to complete thousands of computer transactions.

Packet switching avoids this drawback: it is expressly designed to accommodate the bursty, multiprocess communication commonly found in distributed computing environments. Packets, or chunks of data, produced at the originating computer are prefixed with headers containing routing information that identifies the source and destination computers. Small computers, called packet switches, are linked to form a network. Each packet switch examines each header and decides where to send the packet to move it closer to its final destination. When circuit-switched systems cannot accept new traffic, they refuse to set up new circuits. Packet-switched systems, however, exchange this behavior for variations in delay resulting from storing and forwarding packets. Thus, traffic is not refused, only momentarily delayed.

Packet-switched systems offer another bonus. In circuit-switched systems, the sending and receiving computers must usually be able to exchange data at the same rate, such as 9,600 bits per second or 64,000 bits per second. In packet-switched systems, by contrast, the sender might be able to transmit at very high speeds, such as 10 million bits per second, while the receiver might be able to receive only at low speeds, such as 1,200 bits per second. The automatic speed-matching feature of packet-switched systems allows different types of computer systems, such as supercomputers and personal computers, to communicate. Of course, when two very mismatched computers communicate, the faster one must adapt its average rate of transmission to accommodate the slower.

In addition, because the packet switches are programmable computers, they can detect when the trunk lines linking them have failed and select alternate routes for passing packet traffic without disturbing the source and destination computers. A circuit switch can detect similar failures, but the entire circuit has to be reconstructed in order to recover.

Although packet-switched systems can support communication among processes running in many different

Layers of Communication

APPLICATION	Detailed information about data being exchanged
PRESENTATION	Conventions for representing data
SESSION	Management of connections between programs
TRANSPORT	Delivery (reliable or otherwise) of sequences of packets
NETWORK	Format of individual data packets
LINK	Access to and control of transmission medium
PHYSICAL	Medium of transmission (electronic, optical or other)

computers concurrently, they are not without their problems. In some systems, packets may be routed over multiple paths and arrive in a different order from the one in which they were sent. The receiving computer has to make sure packets are put back in the original sequence (in some systems this service is provided by the receiving packet switch). A disorderly arrival can also occur if a packet is retransmitted because of a detected error.

Another problem is congestion. The packet flow may overtax the storage and forwarding capacity of the switches. If that happens, the switches may be forced to discard packets that cannot be stored or delivered. Detection and prevention of congestion is an important area of packet-switching research.

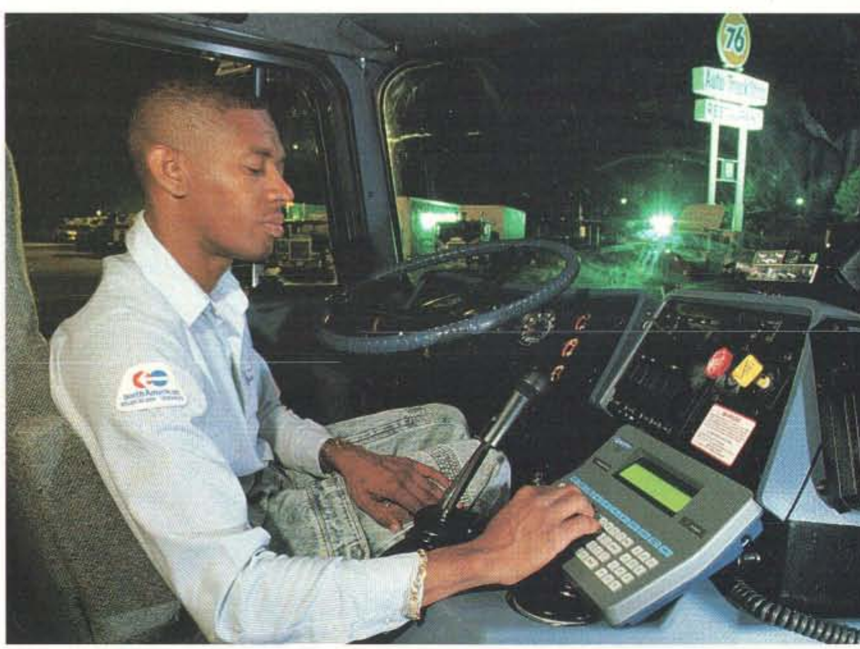
To avoid disorderly arrivals, some packet-switched systems offer a virtual circuit service. In this system the network appears to provide a dedicated circuit to deliver information from one computer to another. In reality, the circuit is virtual, delivering packets in order but with variable delay. Usually the traffic routes are fixed and change only if a failure takes place. If the traffic on each virtual circuit is variable—if the packets emerge from the source in a bursty fashion—then route selection to minimize congestion can still present a challenge. An international standard for virtual circuit packet switching has been codified by the Consultative Committee for International Telephony and Telegraphy (CCITT), an arm of the International Telecommunications Union (ITU). The ITU, which is affiliated with the United Nations, is an international treaty organization.

One of the first packet-switched systems was developed in 1969 under contract to the U.S. Defense Advanced Research Projects Agency (DARPA). Called the ARPANET, the system used minicomputers as packet switches and dedicated 50-kilobit-per-second telephone lines to connect them. Similar projects were also started in other countries, notably the U.K. (the National Physical Laboratory) and France (Institut National Recherche d'Informatique et d'Automatique). Since then, a great many private and public packet-switched networks have been deployed. They typically operate using trunk lines at 56,000, 64,000 or 1.5 to 2 million bits per second.

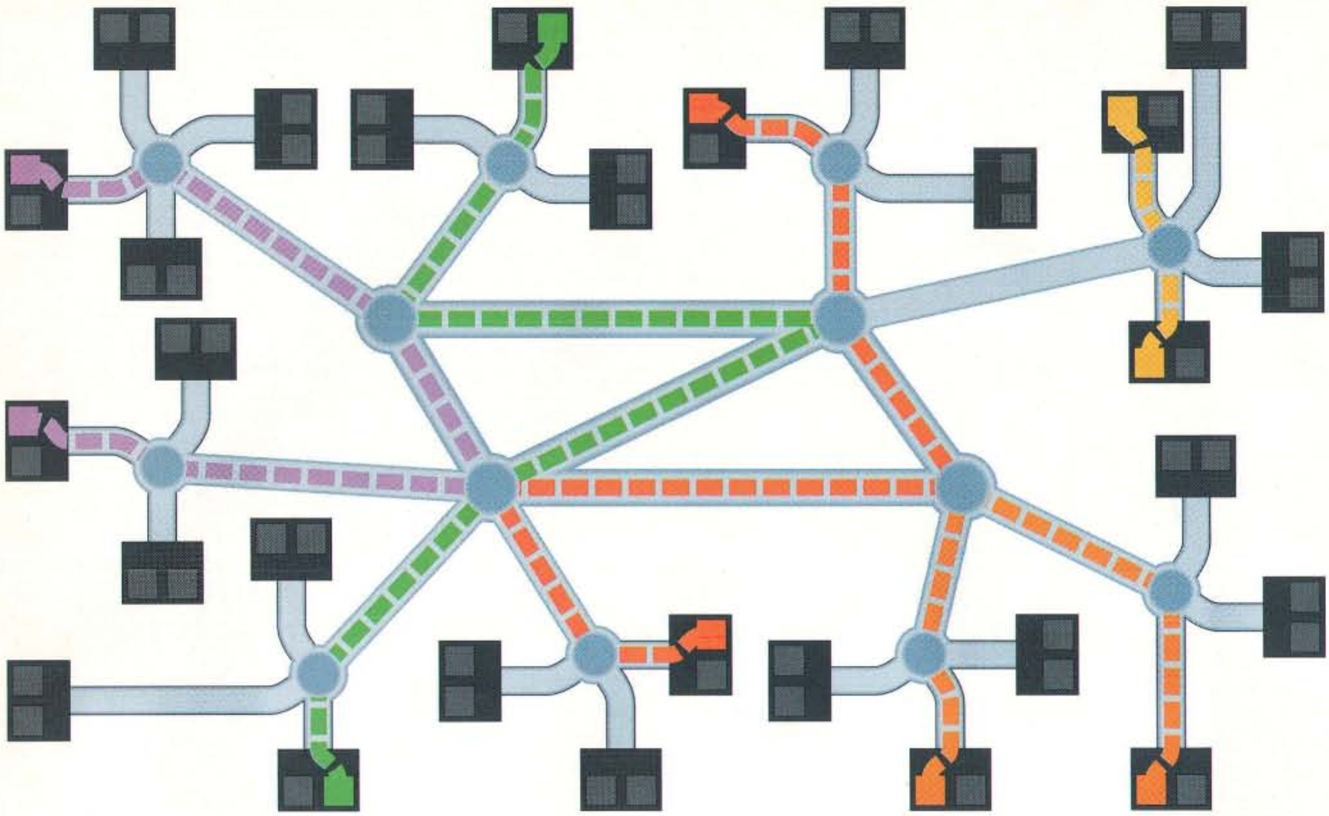
Concurrent with its research on the ARPANET, DARPA also explored packet-switching methods in mobile radio systems and synchronous satellite systems. The ARPANET and its satellite-based counterpart were early examples of so-called wide-area networks (WANs).

Packet-switched systems are used on a variety of transmission media, including local-area networks, metropolitan-area networks, integrated-services digital networks (ISDNs) and networks that operate at gigabit (one billion bits) speeds. One of the first local-area networks to use packet switching was developed in the early 1970s by the Xerox Palo Alto Research Center [see "Networks for Advanced Computing," by Robert E. Kahn; SCIENTIFIC AMERICAN, October 1987]. The system, called Ethernet, is still used today. An Ethernet network transmits signals, which are heard by all receivers (in a broadcast), by coaxial cable over distances of a kilometer or two. Initially operating at three million bits per second, modern Ethernets now work at 10 million bits per second, taking 100 nanoseconds (billionths of a second) to send each bit. Electric signals propagate on the coaxial cable at roughly half the speed of light, or 150,000 kilometers per second. Consequently, one bit can propagate through a 1.5-kilometer network in 10 microseconds.

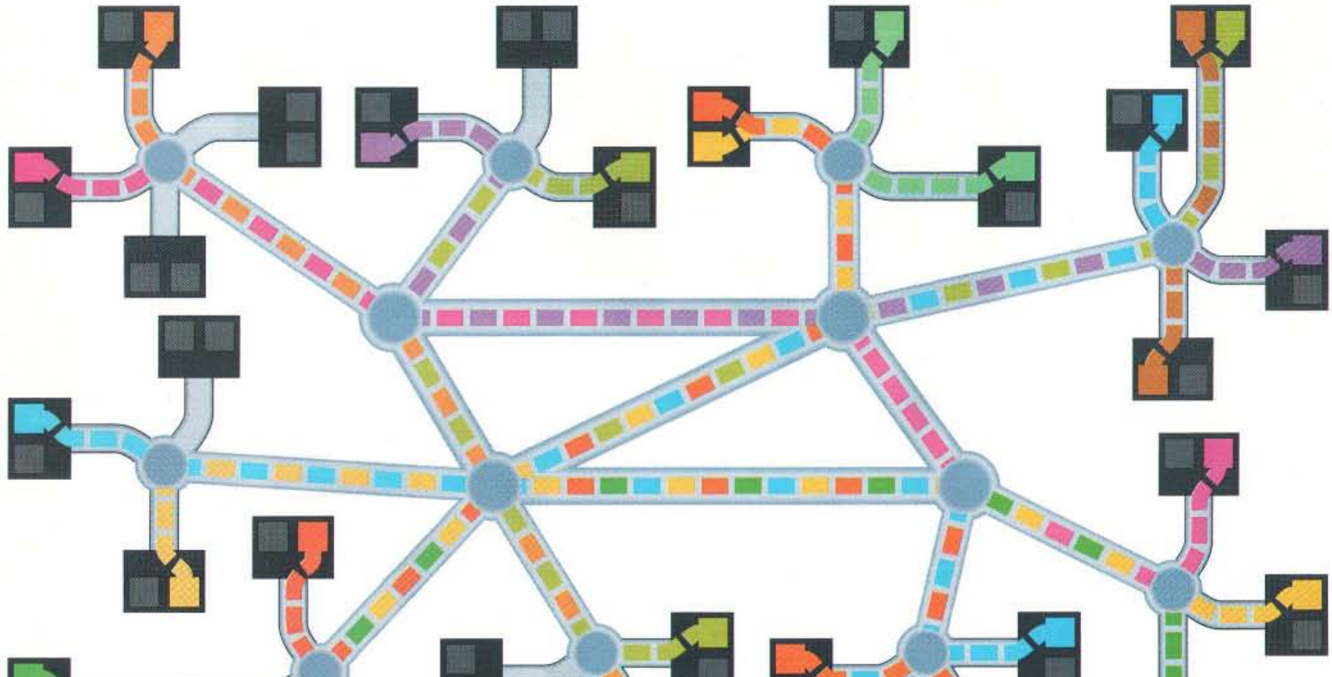
Each transmitter on the Ethernet listens before it transmits. If another transmission is detected, it ceases and waits for a random interval before retrying. This method of channel sharing is called carrier-sense multiple access (CSMA). The Ethernet design cleverly in-



WIRELESS NETWORKS will permit mobile workstations to communicate with the global network. The truck driver in the photograph is using a satellite-based system developed by Qualcomm, Inc., in San Diego, Calif. The system provides instant two-way communication between the trucker and the dispatch center, even on a cross-country run, allowing for unscheduled pickups that reduce "deadhead" miles.



CIRCUIT SWITCHING creates an end-to-end path through the network for data flowing between two computers. This technique, based on methods developed for connecting telephone calls, simplifies data transmission. Yet it is not efficient, because setting up the connection typically takes far more time than transmitting the desired message.



PACKET SWITCHING reduces data transmission overhead by attaching codes (*shown as different colors*) to each item of data sent through the network. The codes identify the source and the destination of each item, so that no end-to-end connection needs to be established. Thus, packets from many different computers can travel easily over the same network links.

cluded a test for competing transmissions *during* transmission so that a collision at the start of sending would cause all colliding senders to stop and wait for a random length of time. The deleterious effect of simultaneous transmissions was thus minimized. If the maximum span of an Ethernet is kept under 1.5 kilometers, collisions, or conflicting transmissions, will be quickly detected and will not consume much capacity on the network. A larger network, however, would suffer a much higher incidence of collision.

A development made in parallel with Ethernet was based on the idea of a ring of computers in which a token, or a short series of bits, is passed from computer to computer. A computer receiving the token is free to transmit one or more packets; other computers must wait until they receive the token to transmit. Token-based systems, which can also broadcast and multicast messages, generally operate at four million to 16 million bits per second.

More recently, packet technologies based on fiber-optic transmission have been developed. They operate at higher speeds and are better suited to larger, metropolitan-area networks. One example is the Fiber Distributed Data Interface (FDDI), which operates at 100 million bits per second and uses a token-based approach to sharing the fiber capacity. The system is organized in a dual ring, so that if a section fails, full operation can be rapidly recovered [*see illustration on this page*]. Token systems can span larger distances than broadcast Ethernets, but the price paid is a longer delay to access the ring. Care must be taken not to introduce more than one token on the ring at a time, although some variations permit multiple tokens to circulate.

A recent development is a fiber-based network technology called Distributed Queue Dual Bus (DQDB) networking. In this design, which works over tens of kilometers or more, nodes are connected to two different fibers, one for each direction. At the originating ends of each fiber, a special node sends out empty packets. The first node that has a packet of data to send fills the empty packet and sends it on its way. When a node has data to send to another node, it sends a request indicator on packets flowing on both fibers. In this way, upstream nodes learn that a downstream node has a packet to send. As empty packets appear, each upstream node allows them to propagate downstream to the node that needs to send data. Each node thus keeps track of the queue of packets awaiting transmission downstream.

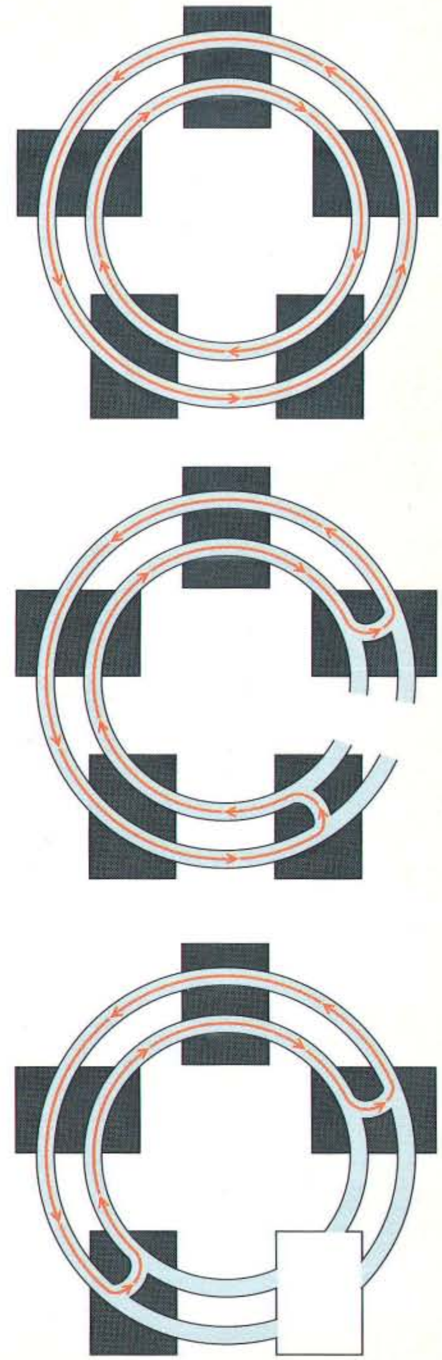
The DQDB technology, which was developed by the University of Western Australia in the mid- to late 1980s, is undergoing trials by local exchange carriers in the U.S. and by telephone administrators in other countries. Because the service is expected to operate at speeds up to 600 million bits per second, it may figure prominently in metropolitan-area networks.

Another recent networking technology is Frame Relay. It is similar in nature to the virtual circuit system, except that the virtual circuits are determined at the time subscribers are connected to the system. No error checking is done as the packets move from switch to switch; there is only end-to-end error checking and retransmission, thereby reducing the delay through the network. Frame Relay, expected to operate in the range of 64,000 to 45 million bits per second, can be used in local-, metropolitan- or wide-area networks.

Over the past 15 years, the telephone carriers have been developing a wide-area digital communications technology, the ISDN, that would permit both voice and data to be carried in digital form across an international, switched digital backbone. ISDN offers two kinds of access to the digital transmission medium. The first, called Basic Rate Interface (BRI), gives a subscriber two bearer (B) channels that operate at 64,000 bits per second each and one data (D) and signaling channel that operates at 16,000 bits per second. The D channel is used to signal the network where to connect each of the B channels. The second is called Primary Rate Interface and operates at 1.5 to 2 million bits per second, providing 23 to 30 B channels.

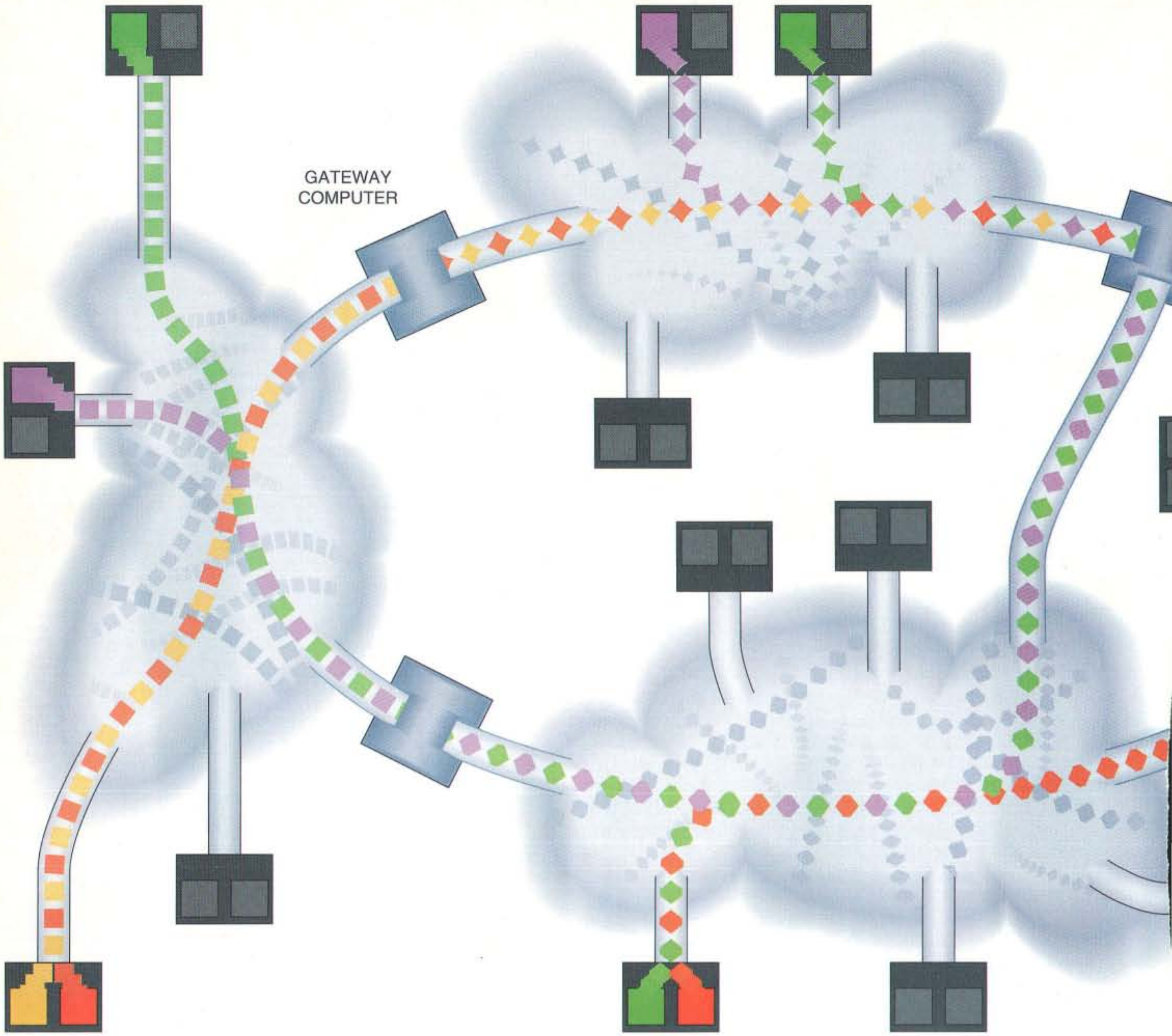
Unfortunately, the service has not been widely deployed, nor has there been a great demand for it. One reason for the cool reception may be that it has been possible to use the voice network to support data communications at speeds up to 19,200 bits per second by employing a device called a modem (modulator-demodulator). The modem turns digital binary signals into modulated sound signals that can be propagated anywhere in the voice network. The difference between 19,200 and 64,000 bits per second is a factor of three, but apparently this difference has not been attractive enough to overcome the cost barrier of having to purchase special equipment to interface with the ISDN network.

An exciting recent development is the emergence of the gigabit-speed network. Local networks operating at speeds in the range of a billion bits per second are now being designed by running parallel connections between com-



DUAL RING (*top*) of the Fiber Distributed Data Interface network helps to safeguard connections against failure. If one of the FDDI optical fibers fails (*middle*) or if a network node ceases operation (*bottom*), the adjacent nodes can readily reconfigure the system to restore full operation.

puters. For example, a ribbon cable containing 64 conductors could sustain an effective data rate of a billion bits per second if each cable carried 16 million bits per second. (Cables carrying 10 to 20 million bits per second are commonplace.) One such system is marketed by Ultra Network Technologies for



INTERNET is a network of networks. Each subsidiary net adheres to a minimal set of common protocols that allow data to pass transparently among computers attached to the Internet, even though the various networks may use different data formats, transmission rates or low-level routing algorithms (represented here schematically by differing data packet shapes).

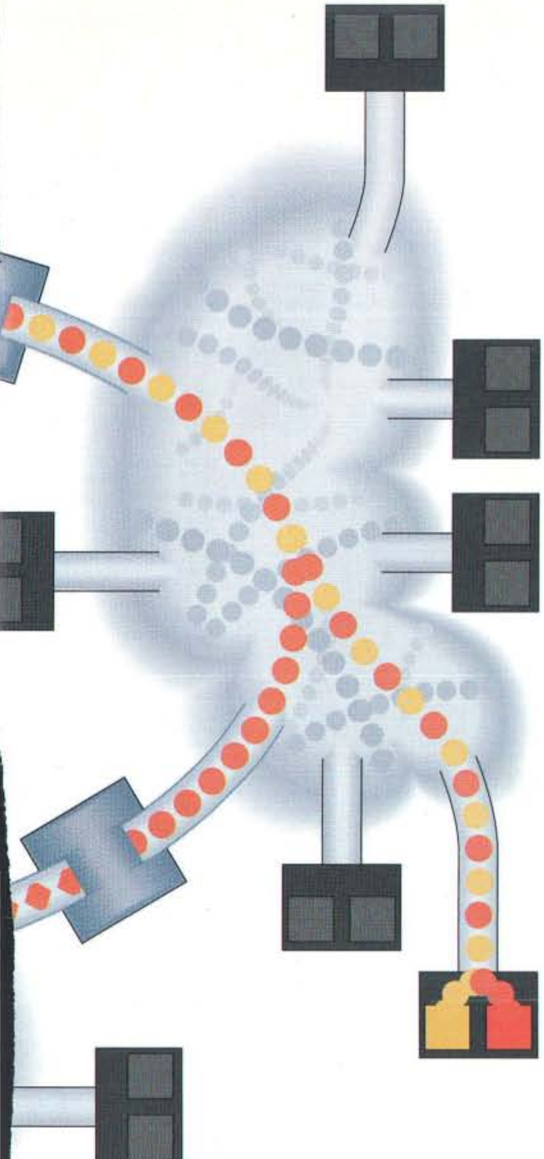
the purpose of linking supercomputers.

For the past few years, fiber-based technologies have been emerging from the laboratory and making their appearance in experimental wide-area settings. These transmission and switching technologies are designed to operate at speeds in excess of a billion bits per second. On the transmission side, the Synchronous Optical Network (SONET) supports a multiplexed hierarchy of transmission speeds ranging from 51 million to 2,400 million bits per second. The SONET system allows data streams of varying transmission speeds to be combined or extracted without first having to break down each stream into its individual components.

Complementing this new transmission technology is a fast packet technique, Asynchronous Transfer Mode (ATM) switching, which can switch short packets called cells at extremely high rates. Cells, which contain up to 48 octets (an octet is eight bits) of data and five octets of addressing and control information, can carry digitized voice, arbitrary data and even digitized video streams.

Conceived as part of a Broadband ISDN (BISDN) system design, ATM switches and SONET fiber transmission technologies may well become the 21st-century equivalent of the 20th-century telephone network. BISDN offers the promise of a common network for all information and communications services, rather than special networks for different services, such as voice, data and video. Already several experimental test-beds, sponsored by DARPA and the National Science Foundation, are exploring applications and architectures for building wide-area gigabit networks.

In addition to the high-speed network developments under way, researchers are working on wireless digital networks that will permit mobile workstations to be part of the global



network. Wireless local-area networks capable of transmitting 10 megabits per second within a room or building are already available, and experimental systems offer far greater bandwidth.

The wireless component of the global net will bear some resemblance to a cellular telephone network—computers carried in trucks, ships or briefcases will be able to maintain connections and send and receive data wherever they go—but current cellular technology is not appropriate for wireless data transmission. First, cellular telephones rely on analog broadcast techniques, so that using them to move digital data would be inherently inefficient. Digital information would have to be converted to analog form for wireless transmission, much as computers now employ modems to send data over ordinary telephone lines.

Second, existing cellular networks are already unable to process the full load of calls that their users desire, much less additional data traffic. A single telephone "cell," typically several miles across, can handle only 59 connections at a time. A few dozen cellular modems could easily block out almost all other callers.

Third, even under the best of circumstances, the frequencies assigned to the cellular telephone network can provide data transmission rates of no more than 100,000 bits per second—insufficient for many potential mobile applications. A wireless complement to existing and future global networks will require new technology, massive capital investment and regulatory changes to allocate sufficient space for data transmission in the electromagnetic spectrum.

Although it may not be apparent, the various technologies I have described can be organized into an architectural hierarchy. Such a conceptual base helps in designing new computer communications technology. Since any computer communications system is based on its protocols, it is not surprising that the conceptual structure is a protocol hierarchy. From the bottom up, the layers can be labeled physical, link, network, transport, session, presentation and application [*see top illustration on page 75*].

The physical layer has to do with the actual medium of electronic, radio frequency or optical transmission and the way in which bits are signaled on the medium. The link layer determines how sequences of bits are framed into chunks. The network layer deals with packet communication and is typically the lowest level at which computer programs can communicate.

The transport layer is the first one at which end-to-end flow and congestion control between communicating programs are regulated. Some applications require that data be delivered in sequence, with high reliability. Others require only that data be delivered expeditiously—some information can be lost. For example, voice or video packets can be made to work if the delays are minimal and the arrival time between packets is short. A lost speech or video packet might introduce a brief gap, but if gaps are infrequent, listeners and viewers can ignore the problem. On the other hand, a file containing a computer program must arrive intact, and an accurate and sequenced delivery is essential.

The layers above transport are closer to the applications and often reflect their needs. Associations between communicating programs are established at the session layer. Conventions for representing information to be exchanged are determined at the presentation layer. Spanning all the layers is the management layer, since management pervades all aspects of networking, from the lowest level to the highest.

In nearly all the discussion so far, I have focused on the first three protocol layers—physical, link and network. I now move to the higher layers—and straight into the important concept of networking the networks, a procedure called network interconnection, or internetting.

Internetting was first explored in the early 1970s by DARPA. The agency sought ways to interconnect different kinds of packet networks so that the computers using them could communicate without concern for which kind of and how many networks made the interconnections. Special processors called gateways were developed to connect two or more networks and to pass packet traffic from one network to the next. Gateways were also responsible for dealing with network differences, such as speed, maximum packet length and error rates [*see illustration on these two pages*].

An internet gives each of its users an address and defines a standard packet format. To send information, a computer creates packets including the source and destination addresses and encapsulates the packets in the format required by the underlying network. The computer then routes the packets to the appropriate gateway or host for further processing, and this series of operations is repeated until the packets reach their final destination.

Many of the same problems that arise in ordinary networks arise in internets. Gateways need routing algorithms so that they can determine the topology of the relevant parts of the internet and decide where internet packets should be sent. Changes in topology caused by network failures and gateway crashes must be accommodated. Control of flow and congestion in an internet pose as much of a challenge as they do in lower-level networks.

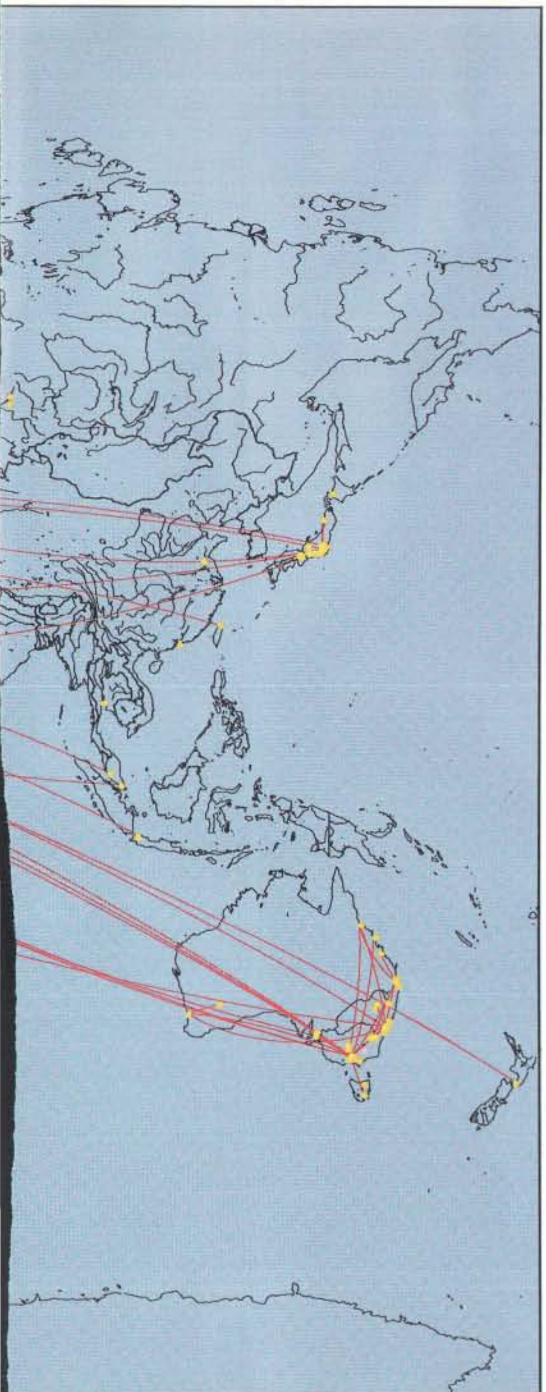
In the boiling ferment of modern telecommunications technology, a critical challenge is to determine how the internetting architecture developed over the past 15 years will have to change to adapt to the emerging gigabit-speed ATM, BISDN and SONET technologies of the 1990s. DARPA and the National Science Foundation are sponsoring

USENET, a worldwide, voluntary member network, has approximately 37,000 nodes (about one tenth the size of the Internet). Accessing electronic mail and other network services requires only finding another Usenet site that is willing to supply a connection.

a major test-bed program to examine this problem through the exploration of experimental applications requiring such superhigh-speed networking. Supercomputer simulation imagery ("visualization"), multiple supercomputer computations and medical and geophysical image generation are all being used to test protocol designs, architectural alternatives and programming environments.

A number of proprietary internetting technologies have been developed by Xerox (the Xerox Network System), Digital Equipment Corporation (DECnet Network Architecture, or DNA) and IBM (Systems Network Architecture and Systems Network Interconnection). DARPA initiated one of the largest open-network systems, the Internet. It operates in 26 countries, comprises more than 5,000 networks and supports several million users on more than 300,000 computers in several thousand organizations. In the U.S., the Internet system has strong support from DARPA, the National Science Foundation, the National Aeronautics and Space Administration and the Department of Energy.

Operating a complex and large-scale computer network or collection of computer networks is a complicated enterprise. As the number of devices involved in the system increases, the system's complexity grows exponentially. Detecting and repairing software, machine and communications



link failures are extremely difficult. As might be expected, network management is a major target for research and development.

A crucial area of network management concerns the security of the system at all levels. Users of remote resources must be satisfactorily identified—typically, by means of a password. Unfortunately, this approach is weak, in part because passwords are not chosen well (they are often last names, names of spouses, license plates and birth dates, for example) and in part because passwords are carried without special protection across the network and thus may be observed by those technically equipped to do so.

The need for security and, in particular, authentication arises at all levels of the protocol hierarchy. At the top level, users may want assurance that electronic mail is coming from the person purported to be the sender; processors may need to know, for accounting purposes, which other systems are consuming resources or, for access-control purposes, which systems are accessing information. In financial transactions, it is critical to assure integrity (that is, to make sure there has been no tampering with a message). For example, one would like to be certain that a deposit is not surreptitiously transferred to another account. In business transactions in which orders are placed, it would be helpful if it were difficult to repudiate confirmed orders.

At lower layers, gateways and routers need to know that control commands are coming from legitimate network management stations. In addition, sometimes information exchanged on the network, such as medical records and electronic mail, needs to be kept confidential. In other cases, it is critical that information such as financial transactions, business orders, network-control information and accounting records not be altered in transit.

Digital cryptography can often satisfy these various requirements. The National Institute of Standards and Technology sponsored the development of a Data Encryption Standard (DES) in the mid-1970s for commercial and government users who did not require military-level cryptography. During the same period, the concept of public key cryptography (PKC) was developed.

In conventional cryptographic systems, a single key encrypts and decrypts messages between parties who wish to keep their communication private and who want assurance that only parties who hold the keys are able to communicate. The DES algorithm is a conventional system: any party holding the key can encrypt or decrypt messages. Such a system is sometimes called a symmetric keying system, since all parties use the same keys, and the same cryptographic algorithm serves for both encryption and decryption.

Public key systems, in contrast, use a pair of keys [see "The Mathematics of Public-Key Cryptography," by Martin E. Hellman; SCIENTIFIC AMERICAN, August 1979]. Messages encrypted in one key can be decrypted only with the other key. It does not matter which key is used to encrypt, only that the other key must be used to decrypt. This form of cryptography is sometimes called an asymmetric keying system.

Typically a user of a public keying system will keep one key private and publicize the other (hence the term "public key system"). To transmit a confidential message to a recipient, the sender encrypts the message in the recipient's public key. Only the recipient can decrypt the message, since only the secret key is useful for that purpose.

An interesting twist to public key cryptography is the digital signature. To "sign" a message, the sender encrypts the message in the secret key. The recipient is given the encrypted message and the advice that it came from the sender. The recipient looks up the sender's public key and uses it to decrypt the message. If the decryption is successful, the recipient knows that the message came from the sender, since only the sender has the secret key that matches the public one. Clearly, digital signatures can be exploited for various transactions (including network management exchanges) in which it is important to verify the source of the message. More important, they allow commerce that would otherwise suffer from serious threats of abuse.

In its book on computer and network security, *Computers at Risk*, the National Research Council opens the first chapter with the alarm, "We are at risk." This is a fair assessment for heavily networked computer systems operating in many countries and with large numbers of programs running concurrently. Technologies for ameliorating that risk are emerging from the research community. If we are at risk, we are also forewarned and, increasingly, forearmed with powerful methods for protecting the system.

FURTHER READING

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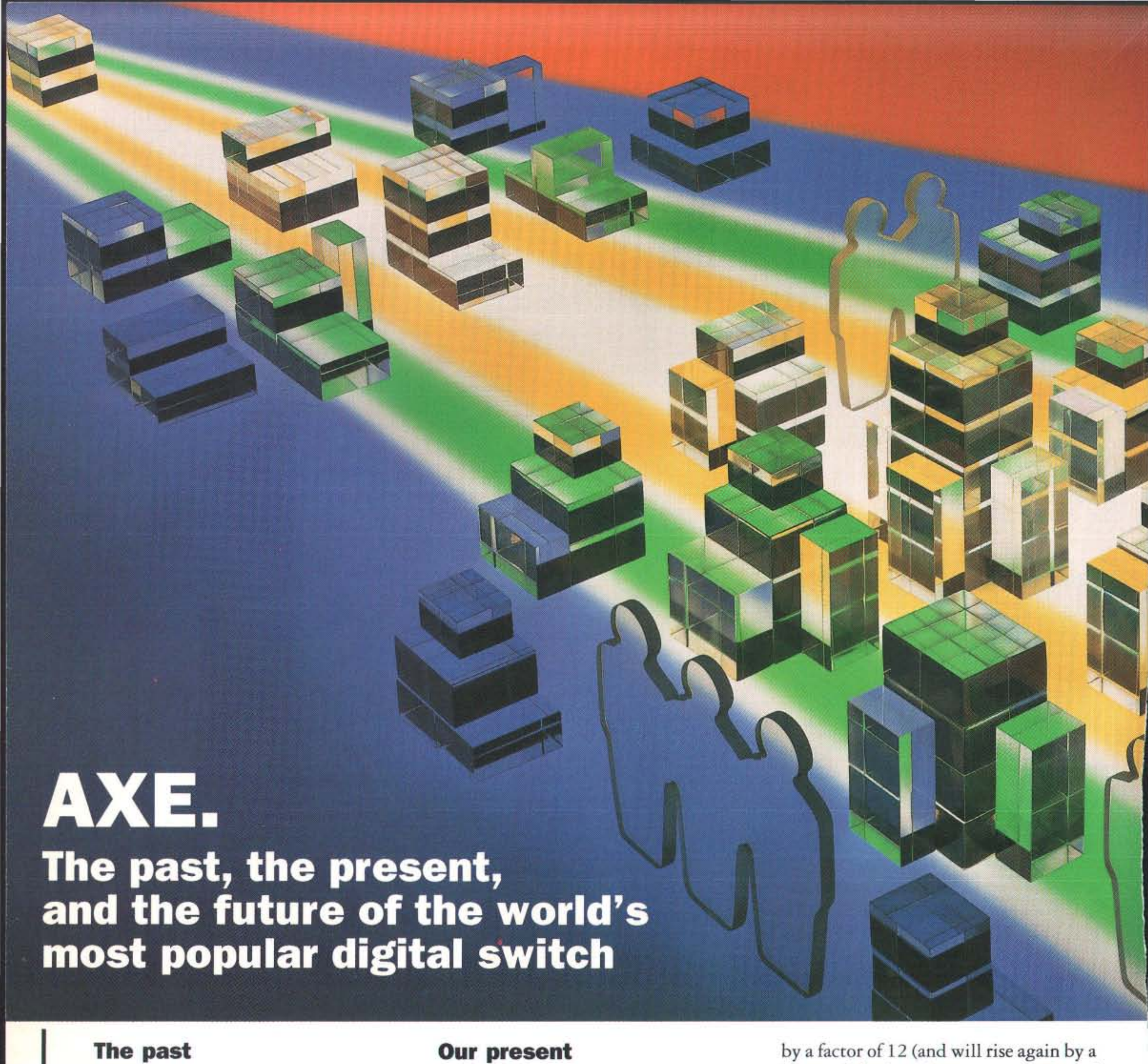


AXE.

The past, the present, and the future of the world's most popular digital switch

The past

Fifteen years ago, Ericsson's AXE digital switch was launched.

It was the first digital switch in the world to handle useful numbers of customers as a local telephone exchange.

It was the first digital switch to be 'designed by the market' – to incorporate solutions to the demands for high traffic capacity and low handling costs.

It was the first digital switch to incorporate a purpose-built real-time computer designed to fit telephony requirements – Ericsson recognised that the commercial computers were unsuitable.

Its architecture was of a thoroughgoing modularity, in hardware and software, that has never been surpassed.

Our present

Today, AXE is the most popular switch in the world – a system choice in more than 80 countries.

There are over 43 million lines of AXE installed or on order, and the rate of ordering is higher than ever.

Why?

The answer is in the basic architecture of AXE – which makes any AXE switch a modular *platform.*

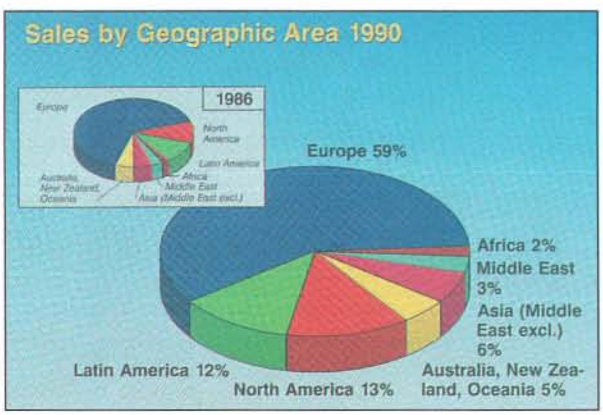
Its modularity means that it never goes out of date. Instead, as new technology emerges, it can be incorporated in or replace any module without disturbing the system. As a result, though virtually no part of AXE is the same as it was fifteen years ago, there has been no break with the past. Processing power has risen by a factor of 12 (and will rise again by a factor of 6 when the next generation of processors is introduced) ... space and power requirements have shrunk dramatically ... the services AXE supports have widened from those of a local exchange to support international switching, cellular mobile telephony, business communications and Intelligent network functions ...

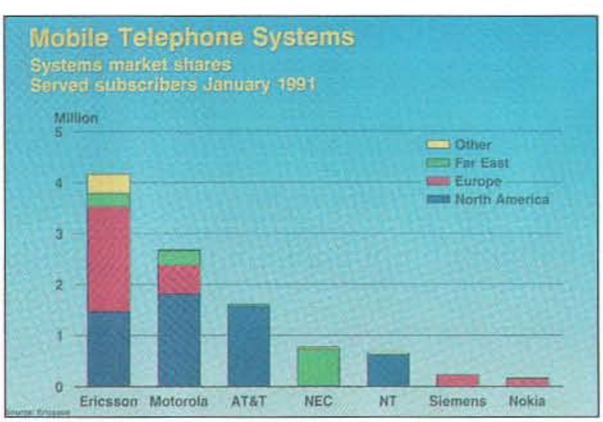
Yet AXE is – and will be – still one system, with one architecture.

AXE has been swift to penetrate the world's most advanced markets. In the USA, Ericsson is a major supplier to most Regional Bell Operating Companies. In Europe, AXE is an approved system for eleven of the twelve EEC members.

the U.S., SS 7, equal access, subscriber services and billing systems. The firm's global reach not only sees expertise cross borders but builds brainpower in all those places Ericsson is present. In a world recession in which massive purchases have often been delayed, Ericsson has increased its technological development costs by SEK 500 million (about US$ 80 million) compared with the first quarter of last year.

Ericsson is organized into six business areas (see chart) of which "public telecommunications" and "radio communications" account for about 70% of sales. Where these intersect — when the telephone becomes a personal belonging, travelling with the user — Ericsson is far out front. It is radio-based communication that is expected to grow the fastest in this





decade, and in three modes: mobile telephone systems (cellular), personal systems (called UPTs — "Universal Personal Telephone") and "radio local loop" — the use of radio instead of permanent lines of communications. Here Ericsson is unique, combining switching, network systems, network management and radio competence. In North America, a most difficult market for non-US companies to win over, the firm has mobile telephone systems in operation in over 80 cities, and a market share close to 30 percent and growing. All in all, the AXE system is in six out of seven regional Bell networks.

Meurling: "Among the trends we follow, two are of outstanding importance: broadband and radio. The first will lead to FTTH ("Fiber to the Home"), allowing for telecom services plus cable TV, energy control, meter reading, high-speed data services, etc. As for radio, in which we are a long-standing leader, the goal is the telephone attached to the person and not to the place." Needed to make it click is a combination of switching and radio technologies — network intelligence in the form of network data bases and network management.

Ericsson's strategic lead in cellular is attributable to this special mix: its status as the only major supplier combining switching, radio and telecommunications networking expertise. In addition, radio base stations and central switching knowledge. All these are in-house at Ericsson. The company's mastery of these fundamentals has allowed its customers to increase their markets with both new subscribers and new services. On a global basis, four in ten of the world's cellular users are supported by Ericsson systems. That is an achievement that must be measured against giants in Japan and the US, for example, with enormous home markets, an advantage Ericsson never has enjoyed. "We are, then, a unique global telecommunications equipment supplier," says Karl A. Alsmar, Senior Vice-President / Product Management. "The network competence, allied to that in switching and system technologies and our mobile communications background — radio — add up to a sustainable competitive advantage."

Networked Computing in the 1990s

Computers began as cumbersome machines served by a technical elite and evolved into desktop tools that obeyed the individual. The next generation will collaborate actively with the user

by Lawrence G. Tesler

In the 1970 film *Colossus: The Forbin Project,* a computer climbs to world domination from the caverns of a hollowed-out mountain, where cabinets decked with flashing lights and spinning tape drives are tended by an army of white-coated programmers.

The stereotype changed between 1977 and 1982, when personal computers entered homes and offices. The new reality was reflected in movies soon afterward: the 1987 film *Wall Street,* for example, portrayed a machine that had shrunk to desktop size, its lights and tapes replaced by a cathode-ray tube, a keyboard and a mouse (that is, a roller that manipulates a pointer on the screen). The priesthood of programmers had vanished, to be replaced by a single user—in this case an investment banker—for whom the computer was a tool, not a calling.

Movies of the 1990s will portray the machines as inconspicuous devices—more like watches than clocks. They will have thin, flat screens, microphones or styli instead of keyboards, and wireless transmitters rather than cable-bound modems. Moreover, their relation to the user will change from that of an isolated productivity tool to that of an active collaborator in the acquisition, use and creation of information, as well as a facilitator of human interaction. Of course, these predictions and others I shall presently make reflect my personal views. Most, however, are widely accepted in the computing profession.

It is generally believed, for example, that the computer will come to play a much more active role by collaborating with the user. The collaborating agent may not even be confined to a particular device. It might move, for example, from palmtop to mainframe data base to desktop. The user, moving from office to car to meetings, might give an electronic agent the following tasks:

• On what date in February did I record a phone conversation with Sam?

• Make me an appointment at a tire shop that is on my way home and is open after 6 P.M.

• Distribute this draft to the rest of the group and let me know when they've read it.

• Whenever a paper is published on fullerene molecules, order a copy for my library.

Programmers will make agents seem intelligent by endowing them with certain reasoning capacities. Agents will consult data bases, and when stumped they will ask the user for guidance. They will be rather like a human assistant, except that they will lack intu-

The Four Paradigms of Computing

	BATCH	TIME-SHARING	DESKTOP	NETWORK
DECADE	1960s	1970s	1980s	1990s
TECHNOLOGY	MEDIUM-SCALE INTEGRATION	LARGE-SCALE INTEGRATION	VERY LARGE SCALE	ULTRA LARGE SCALE
LOCATION	COMPUTER ROOM	TERMINAL ROOM	DESKTOP	MOBILE
USERS	EXPERTS	SPECIALISTS	INDIVIDUALS	GROUPS
USER STATUS	SUBSERVIENCE	DEPENDENCE	INDEPENDENCE	FREEDOM
DATA	ALPHA-NUMERIC	TEXT, VECTOR	FONTS, GRAPHS	SCRIPT, VOICE
OBJECTIVE	CALCULATE	ACCESS	PRESENT	COMMUNICATE
USER ACTIVITY	PUNCH & TRY (SUBMIT)	REMEMBER & TYPE (INTERACT)	SEE & POINT (DRIVE)	ASK & TELL (DELEGATE)
OPERATION	PROCESS	EDIT	LAYOUT	ORCHESTRATE
INTERCONNECT	PERIPHERALS	TERMINALS	DESKTOPS	PALMTOPS
APPLICATIONS	CUSTOM	STANDARD	GENERIC	COMPONENTS
LANGUAGES	COBOL, FORTRAN	PL/I, BASIC	PASCAL, C	OBJECT ORIENTED

ition and the ability to improvise. They will, however, be able to identify recurrent patterns in the user's work, inspect incoming messages and take note of deadlines. Armed with such information, agents will often anticipate needs before the user has expressed them or has even become aware of them. A mobile computer might catch up with its user at breakfast time:

• You asked me when you last recorded a phone conversation with Sam. It was on February 27. Shall I play the recording?

• You scribbled a note last week that your tires were low. I could get you an appointment for tonight.

• Laszlo has discarded the last four drafts you sent him without reading any of them.

• You have requested papers on fullerene research. Shall I order papers on other organic microclusters as well?

Although the commands and responses are represented here as typed English sentences, other forms are possible. They might be handwritten or spoken, more or less grammatical and explicit, in other human languages or perhaps in a more rigid computer language (such as SQL, a language designed for querying data bases). They might be specified by checking off options and filling in blanks on a form or by providing terse answers to a series of questions posed by the agent.

The changes in the computer's role—from cloistered oracle to personal implement to active assistant—have come in distinct waves that can be likened to paradigm shifts, the term by which Thomas S. Kuhn, a philosopher at the Massachusetts Institute of Technology, describes revolutions in scientific thought. Computing paradigms are made possible by steady improvements in a variety of technologies, together with a maturation of the market. They seem to happen at intervals of about a decade.

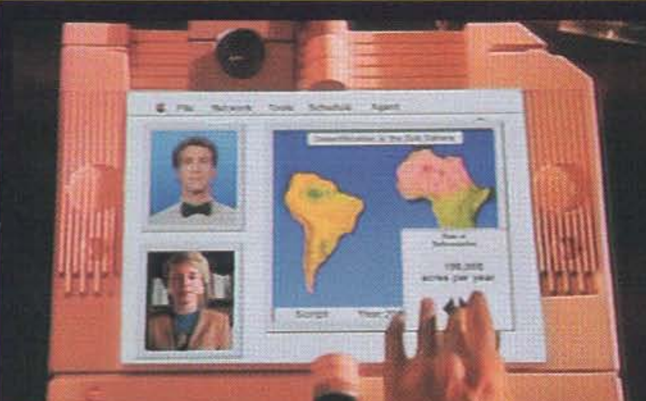
The original computer paradigm was invented in the late 1940s, when the programmable calculator was designed as an engineering tool; it became commercially practical in the 1950s. The first shift came in the 1960s, when the computer was adopted as a data-processing engine by corporations. The second came in the 1970s, when the computer's services were shared among many subscribers. The third shift, in the 1980s, transformed the computer into a desktop productivity tool for individ-

LAWRENCE G. TESLER is vice president of advanced products for Apple Computer Inc. In his former positions with the company, he built a central research group and directed the development of such software products as the applications and user interface for the Lisa computer, the MacApp software development framework and AppleEvents (a mechanism that allows software applications to cooperate in service to the user). In the 1970s Tesler worked at the Xerox Corporation, where he introduced modeless editing and browsing in paned "windows," now a fixture in many interfaces. In the 1960s he managed a small software company, developed easy-to-use animation software and conducted research in cognitive modeling and natural language processing at the Artificial Intelligence Laboratory of Stanford University, his alma mater.

THE IBM 360, circa 1964, processed sequential batches.

THE DECsystem-10, 1975, provided time-sharing.

APPLE COMPUTER'S Macintosh IIci personal computer.

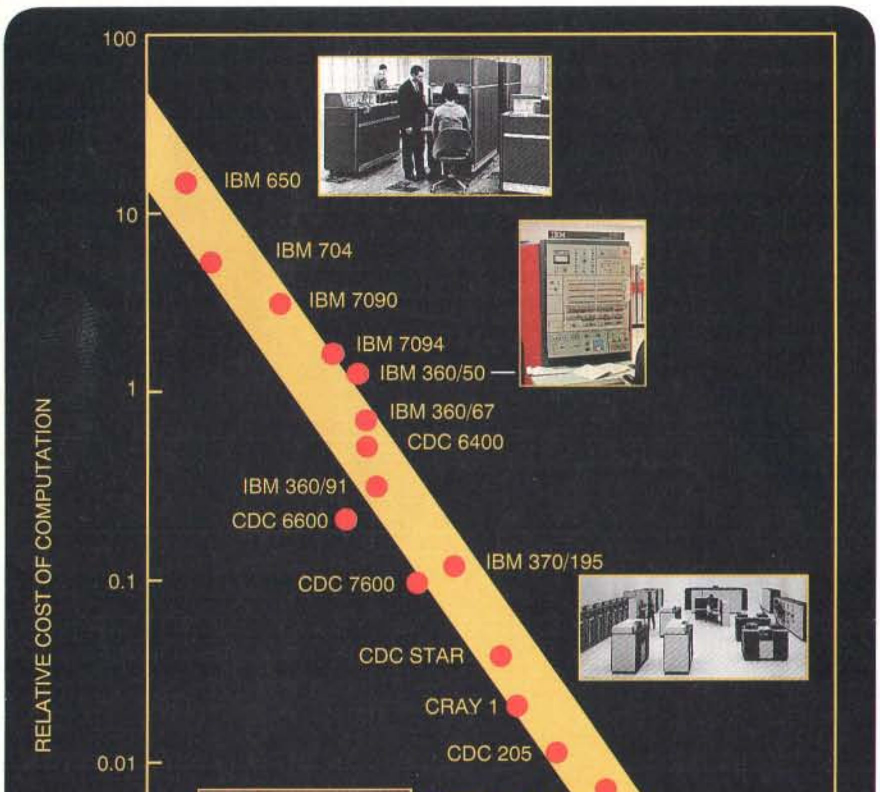


APPLE'S projected software agent: roamer of networks.

uals. The fourth is now under way. Its harbingers are the increasingly networked laptop devices and electronic pocket calendars—mobile machines I call pericomputers. Pericomputers are valuable both for the limited functions they can perform in isolation and for the access they afford to an electronically embodied world of information.

Each shift has fundamentally altered the way people perceive computers. In the 1960s, for example, computing power was dear, and matters had to be arranged at the machine's convenience, as it were. Data had to be processed in huge batches for the technology to pay its way. Only very large organizations could generate such batches. Companies would, for example, run a payroll program to process the week's time cards, then immediately load another "job"—a program with its accompanying data—into the computer. Jobs were coded on punched cards or magnetic tape, and results were delivered as "listings" printed on fanfold, perforated paper. The computer would stop at any error it encountered, in program or data, and return the faulty job to the customer for corrections, a maddening process when reiterated over many hours or even days.

In the 1970s time-sharing made data processing more affordable by allowing many subscribers to split the cost of a computer. This was done by adapting the operating system (by which the computer coordinates its internal activities) so that it divided the machine's attention among such "tasks" as interacting with a particular user terminal. The computer would flit from one task to the next at intervals ranging from less than a tenth of a second to a second or more, depending on the load of work at the time. Computers became easier to use because they could be reached from a terminal and interrogated in real time. That is, one could now work one's way through a problem by asking a question and using the answer to frame the next question.



SOURCE: Victor Peterson, NASA Ames

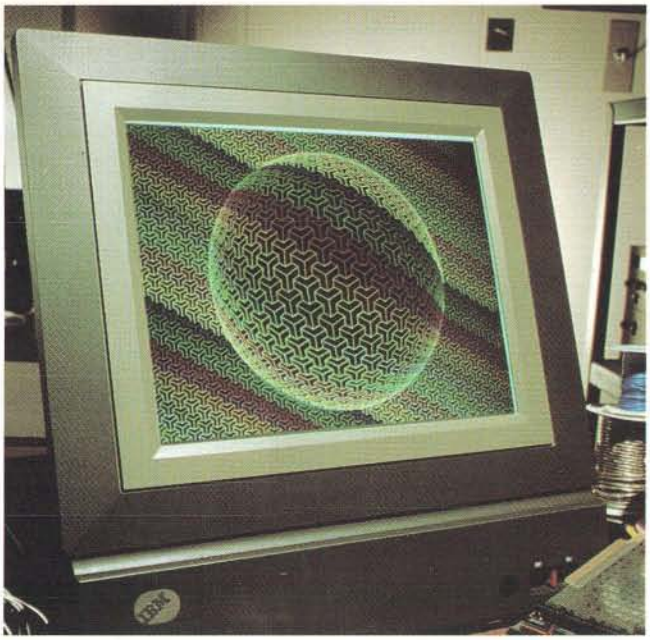
COMPUTING COST has been halved approximately every three years, as indicated in this graph of the most powerful commercial machines of each era.

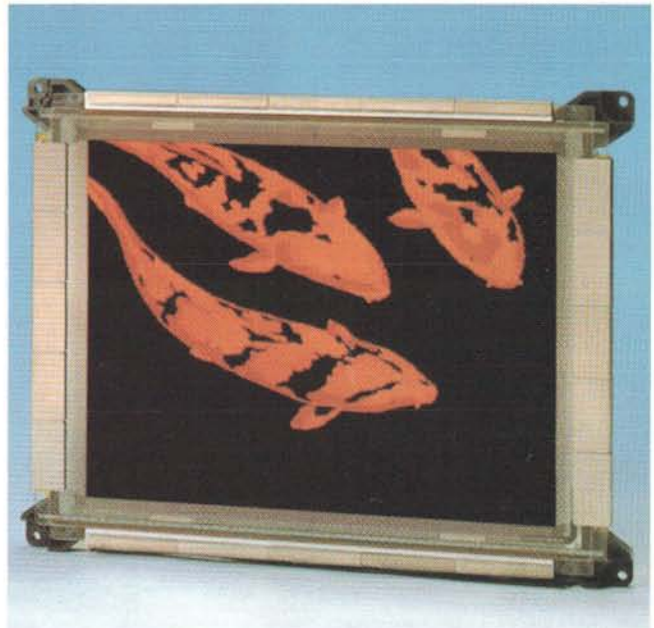
Personal computers initially provided services similar to time-sharing, but with much greater convenience. Advances in microprocessors enabled manufacturers to fit a computer on a single chip, making it cheaper to buy a small computer than share a large one. Now that users no longer depended on costly shared facilities, they could work at will on matters that had previously required scheduling. Word processing and chart creation became routine.

As a result, a new class of users was led through a series of increasingly capable software programs, such as spreadsheet applications and page layout aids, that were made practical by the dedication of unprecedented processing power to one individual. Interrogation also became easier because the burden of keeping track of the possible commands shifted from the user to the computer. Now, for example, various choices are displayed in menus and palettes that one can scan visually before pointing out the desired choice.

For the millions of people who could afford computing power for the first time, the benefits were compelling. They no longer had to retype a page to add one sentence, wait weeks for others to provide them with typesetting or layout service, make a decision based on one or two tediously calculated financial projections or present an exciting idea in a drab form. The new services began as a luxury but quickly became de rigueur, much as typewriting had a century before.

It is important to note that the old paradigms do not necessarily die out completely. In this respect, the evolution of computing recalls that of organisms, which often survive in certain ecological niches even though they have been superseded elsewhere by new forms of life. Time-sharing, for instance, still dominates industries that process many transactions—banking, credit-rating services and airline reservations agencies, for example. New applications have also been developed to take advantage of personal computers. Subscribers





FLAT SCREENS, such as this liquid-crystal display of IBM (*left*) and this plasma display of Fujitsu (*right*), are considered crucial for the development of compact, portable computers. Future designs will have to consume less power.

can use their modems to dial on-line news, shopping and banking services.

Similarly, the hardware associated with mobile computing will not eliminate desktop computers. A computer plugged into a wall socket quite literally has more power than one operated from batteries. A person working at a desk will have occasion to exploit the larger screen and more capacious storage of a larger machine, as well as the faster and more accurate input of a full-size keyboard. Another continuing advantage of fixed computers lies in the vast amounts of information that can be fed to them. Wires can carry more data than radio waves, and optical fiber—the projected successor to wire—will widen the gap. This edge will be felt in desktop conferencing and other data-hungry video applications.

Every era of computing reflects the contemporary speed of computation, the variety of information that can be processed, the ways computers can be linked into networks, the software by which such networks are exploited and the ways in which humans can interact with the devices. Speed, the most basic element, has improved largely through miniaturization.

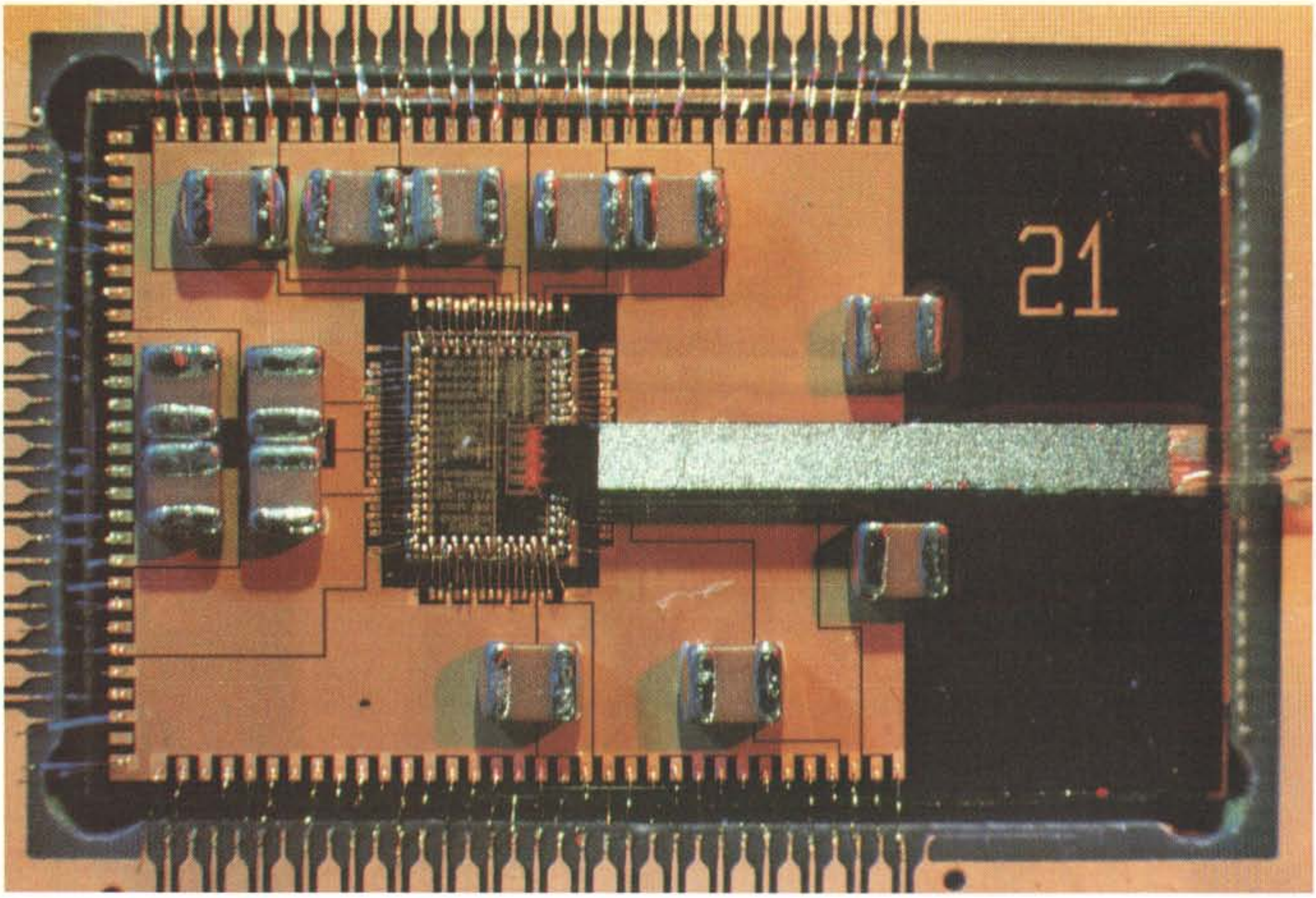
As electronic devices shrink, signals traverse them faster, more operations can be performed in a given period and the cost of computing falls. At the same time, more devices are packed on a chip and thus manufactured in larger batches, reducing the unit cost of manufacturing. Lower costs increase sales, producing additional economies of scale. From the user's point of view, the decline in size yields rapid improvements in usefulness and convenience. Moreover, there is every reason to expect the trend to continue [*see illustration on opposite page*].

Thirty years ago computers were assembled painstakingly out of thousands of transistors and capacitors. Today factories mass-produce computers out of a handful of integrated-circuit chips, each comprising millions of components. In the 1990s, instead of packaging each chip in its own centipedelike, flat package, the semiconductor industry will achieve still higher densities of circuits by producing multichip modules in two and even three dimensions. Stacks of chips will form blocks the size of sugar cubes.

Miniaturization also improves other components of computing systems. Memory, for example, was bulkier than paper as recently as 20 years ago. To store in immediately accessible form a million characters of text (about as many as appear in two copies of this issue of *Scientific American*), one then required a disk pack the size of a birthday cake. By the 1980s that many data could be stored on a diskette that fitted into a shirt pocket. In the 1990s it will be carried on a semiconductor device no larger than a credit card.

New kinds of data become usable with each new paradigm. Early batch-processing systems could manipulate only numbers and uppercase letters. Time-sharing systems made possible interactive document and message editing and often supported vector graphics, which render line drawings on the screen. With personal computers came raster graphics, matrices of dots like the pixels that represent television images. Desktop personal computers already support such media as audio, video, animation and three-dimensional graphics, once the domain of expensive workstations. The coming generation of mobile computers will emphasize facsimile and speech, media that are particularly useful to those who are away from the office.

Networks became important as succeeding paradigms increased the number of computers in service. When batch processors were few, there was little reason to try to make them work in concert. Time-sharing, however, is unthinkable without networks: dedicated or dial-up lines must connect numerous terminals to a host computer, either a corporate mainframe or a departmental minicomputer. The obvious next step was to establish wider networks, among many bank branches, for instance, to make possible the electronic exchange of data. Time-sharing users shared centrally located mass storage facilities and high-speed printers connected to the host. They could post electronic mail messages for other users to see when they next logged in at their terminals. The early terminals were "dumb," that is, they served as mere data links. Lat-



IBM'S EXPERIMENTAL NEXIS CHIP converts signals from optical to electronic form fast enough for computers to exchange data in real time over long distances. Such capabilities will be necessary for advanced networks. The chip integrates four gallium arsenide detectors with the circuitry that amplifies and preprocesses their output signal. The fiber-optic channels (*center*) are made visible by the transmission of red light; infrared light is normally used to minimize energy losses.

er versions incorporated minimal computing power, thus pointing the way to personal computers.

In the desktop computing era, computer networks have assumed new forms. Local-area networks connect personal computers to one another and to shared machines—both general-purpose computers, called hosts, and special-purpose machines, called servers, which provide communal files, high-quality printing and institution-wide electronic mail. Wide-area networks interconnect the various fragments of an enterprise, linking the big machines and file servers to desktop machines. As computers become mobile, wireless connections will proliferate until the information network becomes virtually ubiquitous.

Software applications will also change as mobile computers begin to appear in—or out of—briefcases, purses and pockets. Today's portable machines mainly continue the menu style of interaction, but in the next decade supplementary styles will arise. Transcription software, for example, has already appeared that enables portable machines to display printed versions of handwritten words and polished renderings of roughly drawn figures. Related software recognizes hand-drawn symbols that each represent an entire command or idea. Speech-recognition software that obeys spoken commands is also finding wider application as the technology improves.

Most portable computers now run software written for larger machines, but applications packages are being designed for people who are away from their desks. In such situations, users make notes and sketches but lack the time to compose and edit their jottings. They also exchange information with clients and colleagues, check in with the home office and plan their appointments and how to get to them.

Palmtop machines that perform these functions constitute the first full-fledged pericomputers. So far they cannot compute much, but they suffice for situations into which full-function computers cannot go. One can, for example, work out the day's itinerary on a desktop machine and transfer it to a pericomputer for quick reference. Notes taken in the field can be readied for desktop editing; a pocket calendar and a group calendar can be kept in agreement. Such modest applications will establish a customer base large enough to justify writing a wide range of specialized software. New software will then widen the market.

Software, indeed, will change more than any other element in the computing paradigm. For the first time, it will be written with an eye to the group as well as to the individual. The change reflects the widening of networks, which bring users closer to the work and to one another. It is sometimes hard to remember that until the late 1970s computers were operated by technical experts. They were the trained chefs of the industry: users placed their orders and awaited service. The arrival of personal computers enabled people of all backgrounds to use computers. As in home cooking, more effort was often necessary, but the results, if not always quite up to commercial standards,

were at least fully under one's control.

In five or six years' time it will be as natural to collaborate through a network as it is to prepare a holiday feast with friends in a common kitchen. The software that supports group activity is called groupware; the collaborative activity itself has been dubbed Computer-Supported Cooperative Work. CSCW can be conducted in one place or many, at the same or different times: a meeting in a conference room, a video conference involving distant sites, an electronic bulletin board through which workers on different shifts cooperate or an electronic mail system through which an author and an editor exchange drafts.

When the calendars of the members of an organization are kept on a network server, meeting times convenient to them all can be found automatically by groupware such as Meeting Maker, a product designed by ON Technology in Cambridge, Mass. The initiator selects a time and an available room, types in an agenda and transmits it to prospective attendees. The software invites the people, asks them whether they plan to attend and gives them the opportunity to comment. The initiator of the meeting can reschedule the meeting with ease, literally by dragging a visual representation of the event from one part of the calendar to another with a hand-operated mouse or stylus. The system then notifies the participants of the change.

Whereas Meeting Maker enhances the productivity of a group, other groupware goes further by supporting abstract intellectual collaboration. Engineers in different parts of the world, for example, will be able to design together as if they were standing in front of the same chalkboard. Networked computers can simulate many existing collaboration tools and overcome some of their limitations. A computer can keep an accurate record of a dialogue for later reorganization, editing and distribution. It can ease the construction, viewing, modification and presentation of models in three or more dimensions. It can transport drafts by electronic mail so that each participant can quickly make editing changes. It can keep track of who changed what and merge nonconflicting changes automatically.

When everyone in a brainstorming meeting has a computer and all the computers are on a network, ideas can be captured and displayed in a shared space for all to see, either on their separate computers or on a wall-projected display. Experience at the Xerox Palo Alto Research Center and other CSCW research centers has shown that people judge ideas that appear on a screen more for their value than by the rank of the contributor. An added advantage is that people need not wait their turn or even speak up to be heard [see "Computers, Networks and Work," by Lee Sproull and Sara Kiesler, page 116].

Groupware becomes more worthwhile when wireless communications allows users to gain access to it at will. Such access is crucial: people want to form impromptu working groups in any room, whether or not it has network sockets, and they most need access to group calendars when they are away from their desks. When this becomes practical, other needs will become apparent, too. A person on the move or in a meeting cannot stare at a screen or issue detailed instructions, for example, but it is easy to give a brief command to an infinitely patient and obedient software agent.

Groupware and other network software will in many cases succeed or fail on the basis of how many tenths of a second it takes to respond to a user's query. In many cases, limited products will beat sophisticated ones by getting the job done immediately. This will be especially true of active services, such as those provided by software agents, that guide a person's decisions in real time. A driver who wants to change course to avoid a traffic snarl, for example, cannot wait long for directions.

It is not enough that software be quick to please; it must also be easy to obtain. The marketing trend can already be discerned. Personal desktop computing stimulated a market for generic applications with mass-market appeal, with the result that software publishers now routinely distribute their products on "floppy" disks or pocket-size diskettes through retail outlets and by mail order. When software distribution becomes electronic, people will be able to order a product and load it into their computers in a matter of minutes. There will be less temptation to make illegal copies, which many people do to save not money but time.

Electronic software distribution will also lead vendors to package software into smaller units that can be transmitted more easily. Consumers will compose their own applications out of separately acquired software, analogous to the components of a home audio system. The advent of such "component" software will reverse the past decade's trend toward ever larger, more expensive and harder-to-learn applications. Instead of upgrading from last year's word processor with 20 features to this year's version with 40, a customer can select desired features from a catalog. Those who need a new feature will be able to receive it immediately and, in some cases, automatically. Subscribers to the Prodigy service network already do so: their personal computers receive updated software immediately after the subscriber logs onto the service.

Many hurdles must be cleared before the promise of ubiquitous networks can be fully realized. Several hurdles may constitute serious bottlenecks, a problem familiar in the early stages of previous paradigms. Although aspects of personal computing had been predicted many years beforehand, for example, it took technologies such as the single-chip microprocessor and semiconductor DRAM (dynamic random-access memory) as well as many commercial factors to fulfill the predictions by 1980. For mobile networked computing to become mainstream in the 1990s, a number of technologies will have to advance in terms of their speed, weight, size, ruggedness, cost and consumption of electric power.

Compact, power-thrifty video screens are an absolute necessity for pericomputers. Liquid-crystal displays (LCDs) are the current standard, although they are only now beginning to match cathode-ray tubes in quality. One approach that promises to solve the problem, pioneered independently by RCA Laboratories and by Westinghouse Laboratories, switches liquid-crystal elements so that they polarize light, thus directing it to the proper color filter. Color LCDs and their fluorescent backlights, however, place a major load on the portable battery. New technologies that emit light directly from the screen may provide alternatives that consume less power. One candidate is the field-emission display, which incorporates thousands of microscopic cathodes.

The power drain of a portable computer's electronics places one of the most important constraints on its performance. The devices that require the least power are therefore attracting the most interest. Among them are chips made according to the process of complementary metal oxide semiconductors (CMOSs); systems that operate at a low voltage (say, 3.3 volts, instead of the standard five volts); circuits that employ few chips, thus lessening the charge on interchip wiring; and architectures that use a slow system clock (which paces all components the way a conductor paces an orchestra).

The two most promising architectures wring more speed from less power in quite different ways. One is called RISC (reduced instruction set computer) because it transfers much work from

the hardware to software. Yet most available RISC architectures have been of limited use in mobile machines because they have been designed to optimize performance, not to minimize size and power consumption. One exception is the design of ARM Ltd of Cambridge, England.

The other approach avoids the trade-off between clock speed and power consumption by jettisoning the clock. Such data-flow, or asynchronous, architectures were originally designed to aid in the field of parallel processing. They schedule each processing step to begin only when the necessary data become available. But just-in-time computing introduces great complexities. It is rather like running an orchestra whose members get their cues from one another, rather than from a conductor.

If power is at a premium, one might also try to improve the batteries. The weaknesses of current batteries include the lack of reusability of alkaline designs, the low capacity of nickel-cadmium batteries and the bulk of lead-acid batteries. These weaknesses can sometimes be offset. Miniaturization has improved capacitors, for instance, so that they can accumulate power from low-output sources and supply it in periods of high demand. Software has also been used to drain power automatically from nickel-cadmium batteries before each recharge, thereby averting a permanent loss of storage capacity (or so-called memory effect). New batteries based on nickel-metal hydride and lithium also offer great promise, as do photovoltaic cells, which are already used in calculators. Unfortunately, the conservation of energy makes it impossible for any manageable array of solar cells to supply a backlight bright enough to overcome the sun's glare.

The technologies of handwriting and speech recognition are important because they make mobile computers easier to use. That mission must always be kept in mind; otherwise, one may be tempted to judge a system solely by the number of words it can distinguish or the percentage of errors it makes. Handwriting recognition has been touted for bringing computers into the lives of people who do not like to type. Even those who do like to type cannot do so when standing or holding a machine. In Japan, where the language has a profusion of written symbols that keyboards cannot easily handle, the technology is considered a key selling point.

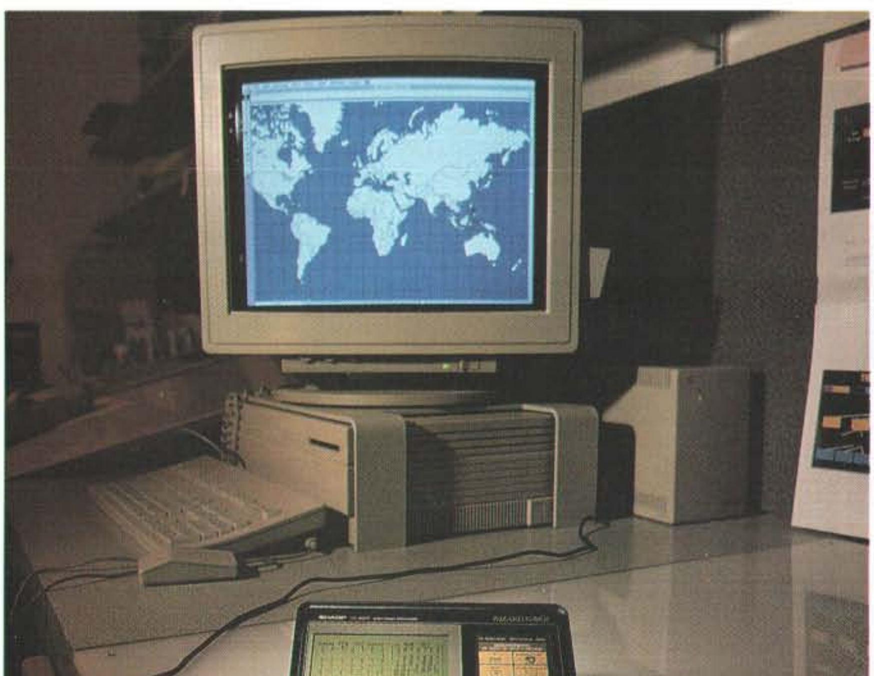
Experience gained with handwriting recognition will be valuable because it can, to some extent, be transferred to speech recognition. Both technologies require, in the more sophisticated applications, a detailed linguistic analysis by which the software raises its chance of recognizing a word or phrase. Both face the challenge of finding where one word ends and the next one begins. Finally, both must be trainable, so that they can adapt their representations of letters or sounds to the handwriting and pronunciation of the user.

Versatile speech recognition requires substantial computing power, but lesser hardware can provide limited capabilities that often prove useful. It is hard to program any computer to take continuous dictation without mistaking the end of one word for the beginning of the next. But it is easy to program even a hand-held computer to distinguish "yes" from "no." A handful of commands may be all most users need to utter when their hands are not free. It has been shown, for example, that mail sorters become much more productive when they call out zip codes instead of dropping their work to fill out a form. Yet this application requires that the system distinguish only 10 words: those for the numerals.

Recognition systems can identify a stroke of the stylus or a trill of the voice by analyzing it into a set of features. Such features can then be compared against a template stored in the computer's memory. Alternatively, the features can be analyzed by neural networks, so called because they mimic the way in which the brain is believed to work. A computer links a digital representation of neurons into a network, then selectively changes the weights assigned to each connection. A process of trial and error then "trains" the system to distinguish various signals.

Another technical challenge to wireless pericomputers is the capacity of the electromagnetic medium itself. To prevent one transmitter from drowning out another, networks within a given building will group transmitters into cells as small as a room. Larger cells will require radio, although local ones may choose infrared light because it uses a part of the electromagnetic spectrum that is not regulated by federal and international authorities.

The limited carrying capacity of that spectrum was exemplified about 10 years ago, when the vogue for citizens band (CB) radio collapsed of its own



PERSONAL ORGANIZER brings networks to the palm of one's hand. These mobile devices can be downloaded directly (*as shown above*) or by telephone.

MASTER AND MAN: the image of the computer has changed with its mode of use. When the machines were expensive and hard to program, they were portrayed as remote tyrants, as in the 1970 movie *Colossus: The Forbin Project*. In this scene, Dr. Forbin is shown leaning against Colossus, the computer that he designed and by which he is finally mastered. Will tomorrow's computer be able to play the benign role of the ideal personal servant—at once ubiquitous and inconspicuous?

weight when users could no longer make themselves heard above the din. Yet that crunch on band space will seem as nothing once mobile computers start blasting megabytes of data across the ether. Even the adoption of a system of cellular relays, such as the one now used for car telephones, might not defer saturation for more than a few years.

Cellular systems will in any case be necessary because mobile machines have to be tracked as they move. If two collaborating users get out of range, the network will have to reestablish the connection transparently through intermediary routing equipment. Even so, there will be times when mobile devices lose contact. Software must therefore be designed so that people affected can easily resume interrupted communication.

No less important than the changes in technology are their human effects. Every new paradigm has molded the way users perceive their status in relation to the computer. In batch and time-sharing days, many users felt subservient; desktop computers gave them independence; mobile networked computers will bring them freedom.

The networked computer will thus challenge not only business but also society. Universal connectivity raises issues of security and personal and business privacy. It also raises the question of the distribution of power. The chasms between rich and poor could widen, for example, if the latest computing paradigm creates still more opportunities for educated people and still fewer for the uneducated.

For reasons of social equity and economic efficiency, it will become more important than ever to educate all people so that they can benefit equally from the information resources that are about to become available. Should the benefits of networks become general, democracy might well be enhanced. Such a pattern can be discerned in Eastern Europe, where the recent revolutions appear to have been helped along by the presence of personal computers, copiers and facsimile transmitters.

The computer, then, has changed much since the days when the movies portrayed it as a relentless superbrain, extending its tyranny to all the world. Its popular image has also changed, albeit with a slight lag. Yet the day is not distant when mobile computers will be common in movies and movie sets alike, where they will manage everything from the scriptwriter's 23rd draft to the key grip's accumulating overtime pay. In that day, art will catch up to life, and the computer will take on a new persona.

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The Computer for the 21st Century

Specialized elements of hardware and software, connected by wires, radio waves and infrared, will be so ubiquitous that no one will notice their presence

by Mark Weiser

The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.

Consider writing, perhaps the first information technology. The ability to represent spoken language symbolically for long-term storage freed information from the limits of individual memory. Today this technology is ubiquitous in industrialized countries. Not only do books, magazines and newspapers convey written information, but so do street signs, billboards, shop signs and even graffiti. Candy wrappers are covered in writing. The constant background presence of these products of "literacy technology" does not require active attention, but the information to be transmitted is ready for use at a glance. It is difficult to imagine modern life otherwise.

Silicon-based information technology, in contrast, is far from having become part of the environment. More than 50 million personal computers have been sold, and the computer nonetheless remains largely in a world of its own. It is approachable only through complex jargon that has nothing to do with the tasks for which people use computers. The state of the art is perhaps analogous to the period when scribes had to know as much about making ink or baking clay as they did about writing.

The arcane aura that surrounds personal computers is not just a "user interface" problem. My colleagues and I at the Xerox Palo Alto Research Center think that the idea of a "personal" computer itself is misplaced and that the vision of laptop machines, dynabooks and "knowledge navigators" is only a transitional step toward achieving the real potential of information technology. Such machines cannot truly make computing an integral, invisible part of people's lives. We are therefore trying to conceive a new way of thinking about computers, one that takes into account the human world and allows the computers themselves to vanish into the background.

Such a disappearance is a fundamental consequence not of technology but of human psychology. Whenever people learn something sufficiently well, they cease to be aware of it. When you look at a street sign, for example, you absorb its information without consciously performing the act of reading. Computer scientist, economist and Nobelist Herbert A. Simon calls this phenomenon "compiling"; philosopher Michael Polanyi calls it the "tacit dimension"; psychologist J. J. Gibson calls it "visual invariants"; philosophers Hans Georg Gadamer and Martin Heidegger call it the "horizon" and the "ready-to-hand"; John Seely Brown of PARC calls it the "periphery." All say, in essence, that only when things disappear in this way are we freed to use them without thinking and so to focus beyond them on new goals.

The idea of integrating computers seamlessly into the world at large runs counter to a number of present-day trends. "Ubiquitous computing" in this context does not mean just computers that can be carried to the beach, jungle or airport. Even the most powerful notebook computer, with access to a worldwide information network, still focuses attention on a single box. By analogy with writing, carrying a superlaptop is like owning just one very important book. Customizing this book, even writing millions of other books, does not begin to capture the real power of literacy.

Furthermore, although ubiquitous computers may use sound and video in addition to text and graphics, that does not make them "multimedia computers." Today's multimedia machine makes the computer screen into a demanding focus of attention rather than allowing it to fade into the background.

Perhaps most diametrically opposed to our vision is the notion of virtual reality, which attempts to make a world inside the computer. Users don special goggles that project an artificial scene onto their eyes; they wear gloves or even bodysuits that sense their motions and gestures so that they can move about and manipulate virtual objects. Although it may have its purpose in allowing people to explore realms otherwise inaccessible—the insides of cells, the surfaces of distant planets, the information web of data bases—virtual reality is only a map, not a territory. It excludes desks, offices, other people not wearing goggles and bodysuits, weather, trees, walks, chance encounters and, in general, the infinite richness of the universe. Virtual reality focuses an enormous apparatus on simulating the world rather than on invisibly enhancing the world that already exists.

Indeed, the opposition between the

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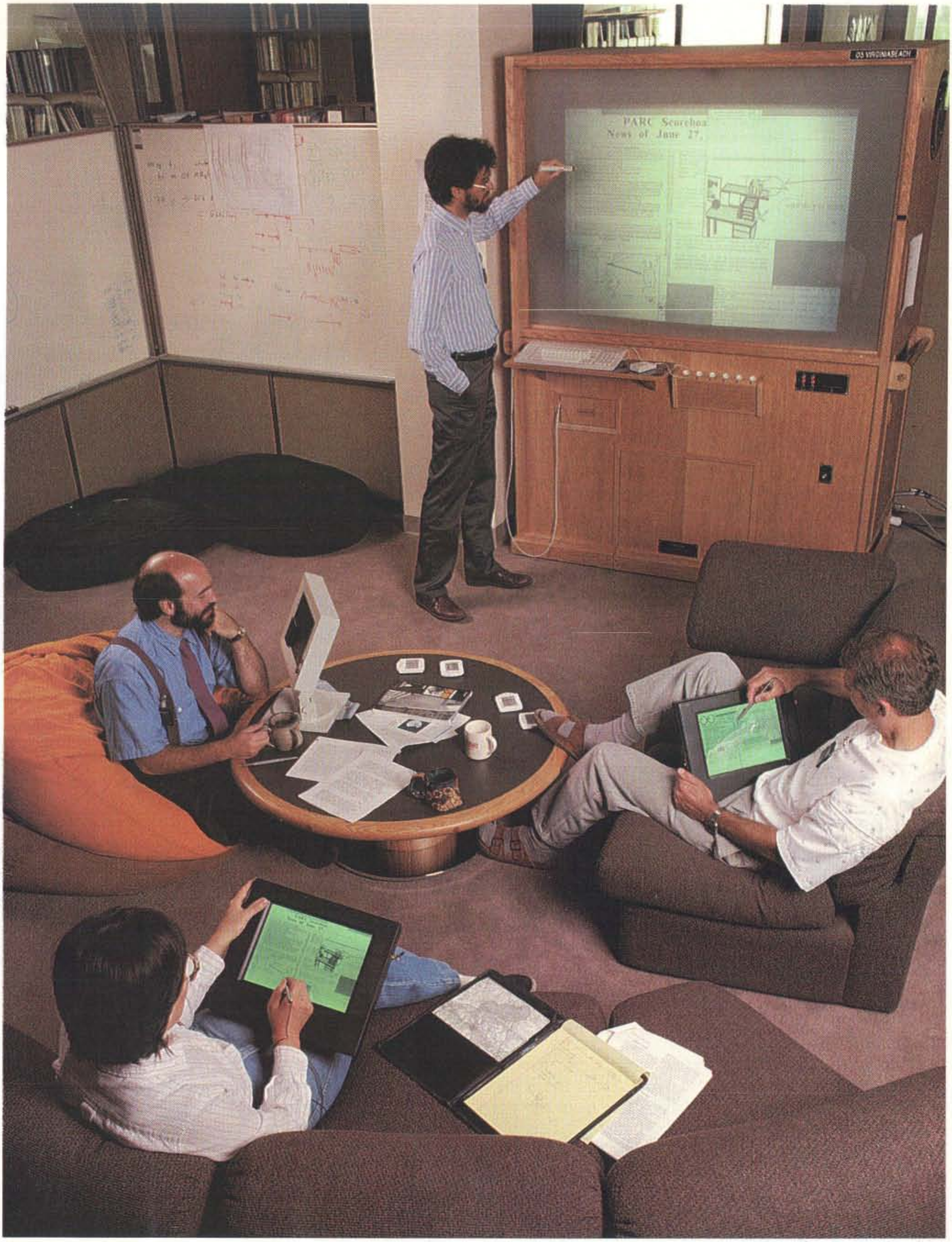
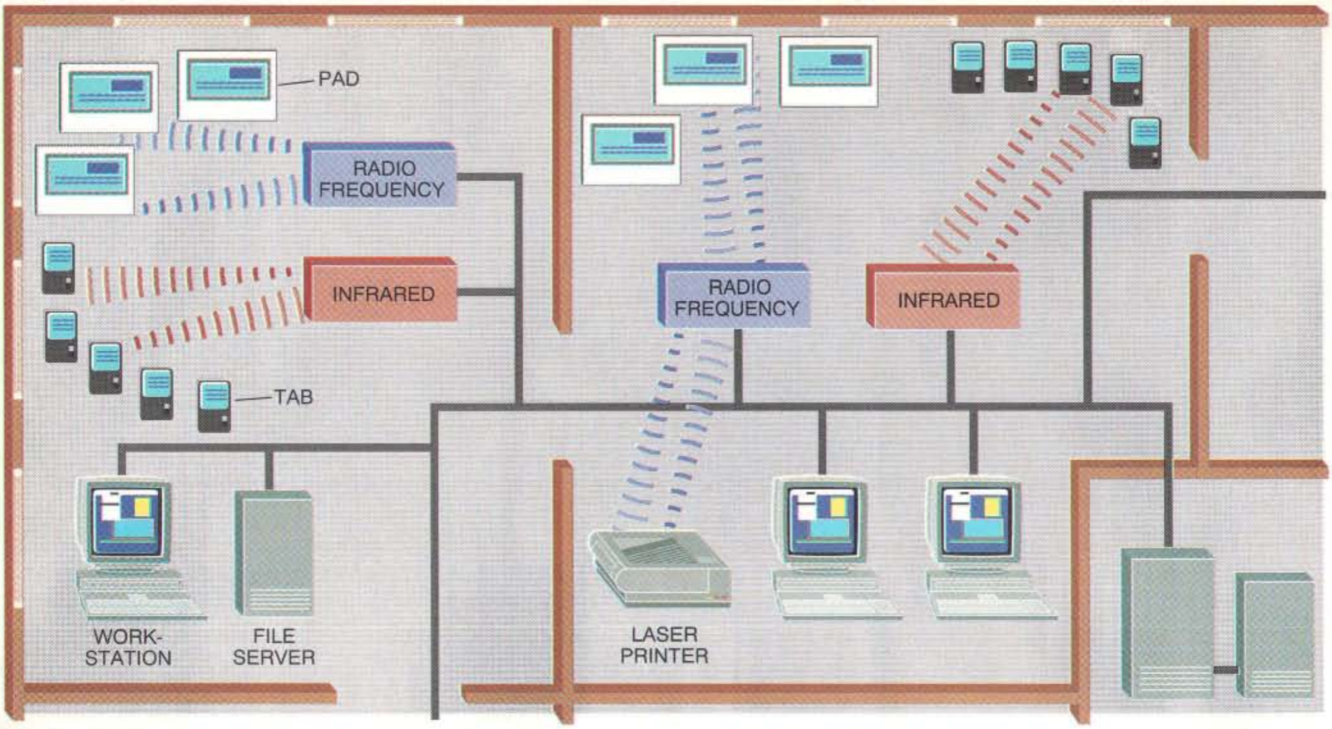


UBIQUITOUS COMPUTING begins to emerge in the form of live boards that replace chalkboards as well as in other devices at the Xerox Palo Alto Research Center. Computer scientists gather around a live board for discussion. Building boards and integrating them with other tools has helped researchers understand better the eventual shape of ubiquitous computing. In conjunction with active badges, live boards can customize the information they display.



WIRED AND WIRELESS NETWORKS link computers and allow their users to share programs and data. The computers pictured here include conventional terminals and file servers, pocket-size machines known as tabs and page-size ones known as pads. Future networks must be capable of supporting hundreds of devices in a single room and must also cope with devices—ranging from tabs to laser printers or large-screen displays—that move from one place to another.

notion of virtual reality and ubiquitous, invisible computing is so strong that some of us use the term "embodied virtuality" to refer to the process of drawing computers out of their electronic shells. The "virtuality" of computer-readable data—all the different ways in which they can be altered, processed and analyzed—is brought into the physical world.

How do technologies disappear into the background? The vanishing of electric motors may serve as an instructive example. At the turn of the century, a typical workshop or factory contained a single engine that drove dozens or hundreds of different machines through a system of shafts and pulleys. Cheap, small, efficient electric motors made it possible first to give each tool its own source of motive force, then to put many motors into a single machine.

A glance through the shop manual of a typical automobile, for example, reveals 22 motors and 25 solenoids. They start the engine, clean the windshield, lock and unlock the doors, and so on. By paying careful attention, the driver might be able to discern whenever he or she activated a motor, but there would be no point to it.

Most computers that participate in embodied virtuality will be invisible in fact as well as in metaphor. Already computers in light switches, thermostats, stereos and ovens help to activate the world. These machines and more will be interconnected in a ubiquitous network. As computer scientists, however, my colleagues and I have focused on devices that transmit and display information more directly. We have found two issues of crucial importance: location and scale. Little is more basic to human perception than physical juxtaposition, and so ubiquitous computers must know where they are. (Today's computers, in contrast, have no idea of their location and surroundings.) If a computer knows merely what room it is in, it can adapt its behavior in significant ways without requiring even a hint of artificial intelligence.

Ubiquitous computers will also come in different sizes, each suited to a particular task. My colleagues and I have built what we call tabs, pads and boards: inch-scale machines that approximate active Post-it notes, foot-scale ones that behave something like a sheet of paper (or a book or a magazine) and yard-scale displays that are the equivalent of a blackboard or bulletin board.

How many tabs, pads and board-size writing and display surfaces are there in a typical room? Look around you: at the inch scale, include wall notes, titles on book spines, labels on controls, thermostats and clocks, as well as small pieces of paper. Depending on the room, you may see more than 100 tabs, 10 or 20 pads and one or two boards. This leads to our goal for initially deploying the hardware of embodied virtuality: hundreds of computers per room.

Hundreds of computers in a room could seem intimidating at first, just as hundreds of volts coursing through wires in the walls once did. But like the wires in the walls, these hundreds of computers will come to be invisible to common awareness. People will simply use them unconsciously to accomplish everyday tasks.

Tabs are the smallest components of embodied virtuality. Because they are interconnected, tabs will expand on the usefulness of existing inch-scale computers, such as the pocket calculator and the pocket organizer. Tabs will also take on functions that no computer performs today. For example, computer scientists at PARC and other research laboratories around the world have begun working with active badges—clip-on computers roughly the size of an employee I.D. card, first developed by the Olivetti Cambridge research laboratory. These badges can identify themselves to receivers placed throughout a building, thus making it possible to keep track of the people or objects to which they are attached.

In our experimental embodied virtuality, doors open only to the right badge wearer, rooms greet people by name, telephone calls can be automatically forwarded to wherever the recipient may be, receptionists actually know where people are, computer terminals retrieve the preferences of whoever is sitting at them, and appointment diaries write themselves. The automatic diary shows how such a simple task as knowing where people are can yield complex dividends: meetings, for example, consist of several people spending time in the same room, and the subject of a meeting is most probably the files called up on that room's display screen while the people are there. No revolution in artificial intelligence is needed, merely computers embedded in the everyday world.

My colleague Roy Want has designed a tab incorporating a small display that can serve simultaneously as an active badge, calendar and diary. It will also act as an extension to computer screens: instead of shrinking a program window down to a small icon on the screen, for example, a user will be able to shrink the window onto a tab display. This will leave the screen free for information and also let people arrange their computer-based projects in the area around their terminals, much as they now arrange paper-based projects in piles on desks and tables. Carrying a project to a different office for discussion is as simple as gathering up its tabs; the associated programs and files can be called up on any terminal.

The next step up in size is the pad, something of a cross between a sheet of paper and current laptop and palmtop computers. Robert Krivacic of PARC has built a prototype pad that uses two microprocessors, a workstation-size display, a multibutton stylus and a radio network with enough communications bandwidth to support hundreds of devices per person per room.

Pads differ from conventional portable computers in one crucial way. Whereas portable computers go everywhere with their owners, the pad that must be carried from place to place is a failure. Pads are intended to be "scrap computers" (analogous to scrap paper) that can be grabbed and used anywhere; they have no individualized identity or importance.

One way to think of pads is as an antidote to windows. Windows were invented at PARC and popularized by Apple in the Macintosh as a way of fitting several different activities onto the small space of a computer screen at the same time. In 20 years computer screens have not grown much larger. Computer window systems are often said to be based on the desktop metaphor—but who would ever use a desk only nine inches high by 11 inches wide?

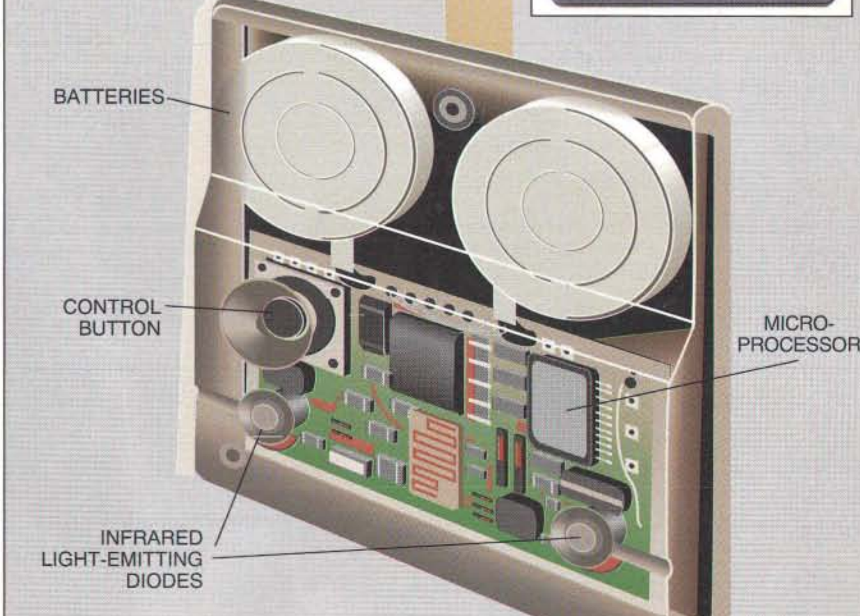
Pads, in contrast, use a real desk. Spread many electronic pads around on the desk, just as you spread out papers. Have many tasks in front of you, and use the pads as reminders. Go beyond the desk to drawers, shelves, coffee tables. Spread the many parts of the many tasks of the day out in front of you to fit both the task and the reach of your arms and eyes rather than to fit the limitations of glassblowing. Someday pads may even be as small and light as actual paper, but meanwhile they can fulfill many more of paper's functions than can computer screens.

Yard-size displays (boards) serve a number of purposes: in the home, video screens and bulletin boards; in the office, bulletin boards, white boards or flip charts. A board might also serve as an electronic bookcase from which one might download texts to a pad or tab. For the time being, however, the ability to pull out a book and place it comfortably on one's lap remains one of the many attractions of paper. Similar objections apply to using a board as a desktop; people will have to become accustomed to having pads and tabs on a desk as an adjunct to computer screens before taking embodied virtuality any further.

Prototype boards, built by Richard Bruce and Scott Elrod of PARC, are in use at several Xerox research laboratories. They measure about 40 by 60 inches and display $1,024 \times 768$ black-and-white pixels. To manipulate the

The Active Badge

This harbinger of inch-scale computers contains a small microprocessor and an infrared transmitter. The badge broadcasts the identity of its wearer and so can trigger automatic doors, automatic telephone forwarding and computer displays customized to each person reading them. The active badge and other networked tiny computers are called tabs.



display, users pick up a piece of wireless electronic "chalk" that can work either in contact with the surface or from a distance. Some researchers, using themselves and their colleagues as guinea pigs, can hold electronically mediated meetings or engage in other forms of collaboration around a live board. Others use the boards as testbeds for improved display hardware, new "chalk" and interactive software.

For both obvious and subtle reasons, the software that animates a large shared display and its electronic chalk is not the same as that for a workstation. Switching back and forth between chalk and keyboard may involve walking several steps, and so the act is qualitatively different from using a keyboard and mouse. In addition, body size is an issue. Not everyone can reach the top of the board, so a Macintosh-style menu bar might have to run across the bottom of the screen instead.

We have built enough live boards to permit casual use: they have been placed in ordinary conference rooms and open areas, and no one need sign up or give advance notice before using them. By building and using these boards, researchers start to experience and so understand a world in which computer interaction informally enhances every room. Live boards can usefully be shared across rooms as well as within them. In experiments instigated by Paul Dourish of EuroPARC and Sara Bly and Frank Halasz of PARC, groups at widely separated sites gathered around boards—each displaying the same image—and jointly composed pictures and drawings. They have even shared two boards across the Atlantic.

Live boards can also be used as bulletin boards. There is already too much text for people to read and comprehend all of it, and so Marvin Theimer and David Nichols of PARC have built a prototype system that attunes its public information to the people reading it. Their "scoreboard" requires little or no interaction from the user other than to look and to wear an active badge.

Prototype tabs, pads and boards are just the beginning of ubiquitous computing. The real power of the concept comes not from any one of these devices—it emerges from the interaction of all of them. The hundreds of processors and displays are not a "user interface" like a mouse and windows, just a pleasant and effective "place" to get things done.

What will be most pleasant and effective is that tabs can animate objects previously inert. They can beep to help locate mislaid papers, books or other items. File drawers can open and show the desired folder—no searching. Tabs in library catalogues can make active maps to any book and guide searchers to it, even if it is off the shelf, left on a table by the last reader.

In presentations, the size of text on overhead slides, the volume of the amplified voice, even the amount of ambient light, can be determined not by guesswork but by the desires of the listeners in the room at that moment. Software tools for tallying votes instantly and consensus checking are already available in electronic meeting rooms of some large corporations; tabs can make them widespread.

The technology required for ubiquitous computing comes in three parts: cheap, low-power computers that include equally convenient displays, software for ubiquitous applications and a network that ties them all together. Current trends suggest that

COMPUTER SCRATCHPADS augment the conventional screen in this office at the Xerox Palo Alto Research Center. Prototype pads are wired to conventional computers; thus far only a handful of wireless models have been built.

the first of these requirements will easily be met. Flat-panel displays containing 640×480 black-and-white pixels are now common. This is the standard size for PCs and is also about right for television. As long as laptop, palmtop and notebook computers continue to grow in popularity, display prices will fall, and resolution and quality will rise. By the end of the decade, a $1,000 \times 800$-pixel high-contrast display will be a fraction of a centimeter thick and weigh perhaps 100 grams. A small battery will provide several days of continuous use.

Larger displays are a somewhat different issue. If an interactive computer screen is to match a white board in usefulness, it must be viewable from arm's length as well as from across a room. For close viewing, the density of picture elements should be no worse than on a standard computer screen, about 80 per inch. Maintaining a density of 80 pixels per inch over an area several feet on a side implies displaying tens of millions of pixels. The biggest computer screen made today has only about one fourth that capacity. Such large displays will probably be expensive, but they should certainly be available.

The large display will require advanced microprocessors to feed it. Central-processing-unit speeds reached a million instructions per second in 1986 and continue to double each year. Some industry observers believe that this exponential growth in raw chip speed may begin to level off about 1994 but that other measures of performance, including power consumption and auxiliary functions, will still improve. The 100-gram flat-panel display, then, might be driven by a microprocessor that executes a billion operations per second and contains 16 megabytes of on-board memory along with sound, video and network interfaces. Such a processor would draw, on average, a few percent of the power required by the display.

Auxiliary storage devices will augment main memory capacity: conservative extrapolation of current technology suggests that removable hard disks (or nonvolatile memory chips) the size of a matchbook will store about 60 megabytes each. Larger disks containing several gigabytes of information will be standard, and terabyte storage—roughly the data content of the Library of Congress—will be common. Such enormous stores will not necessarily be filled to capacity with usable information. Abundant space will, however, allow radically different strategies of information management. A terabyte of disk storage will make deleting old files virtually unnecessary, for example.

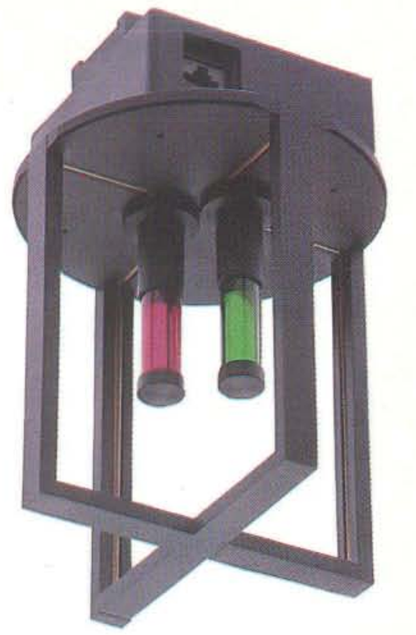
Although processors and displays should be capable of offering ubiquitous computing by the end of the decade, trends in software and network technology are more problematic. Current implementations of "distributed computing" simply make networked file servers, printers or other devices appear as if they were connected directly to each user's computer. This approach, however, does nothing to exploit the unique capabilities of physically dispersed computers and the information embodied in knowing where a particular device is located.

Computer operating systems and window-based display software will have to change substantially. The design of current operating systems, such as DOS and Unix, is based on the assumption that a computer's hardware and software configuration will not change substantially while it is running. This assumption is reasonable for conventional mainframes and personal computers, but it makes no sense in terms of ubiquitous computing. Pads, tabs and even boards may come and go at any time in any room, and it will certainly be impossible to shut down all the computers in a room to install new software in any one of them. (Indeed, it may be impossible to find all the computers in a room.)

One solution may be "micro-kernel" operating systems such as those developed by Rick Rashid of Carnegie Mellon University and A. S. Tanenbaum of Vrije University in Amsterdam. These experimental systems contain only the barest scaffolding of fixed computer code; software modules to perform specific functions can be readily added or removed. Future operating systems based on this principle could shrink and grow automatically to fit the changing needs of ubiquitous computation.

Current window display systems also are not ready to cope with ubiquitous computing. They typically assume that a particular computer will display all the information for a single application. Although the X Window System and Windows 3.0, for example, can cope with multiple screens, they do not do well with applications that start out on one screen and move to another, much less those that peregrinate from computer to computer or room to room.

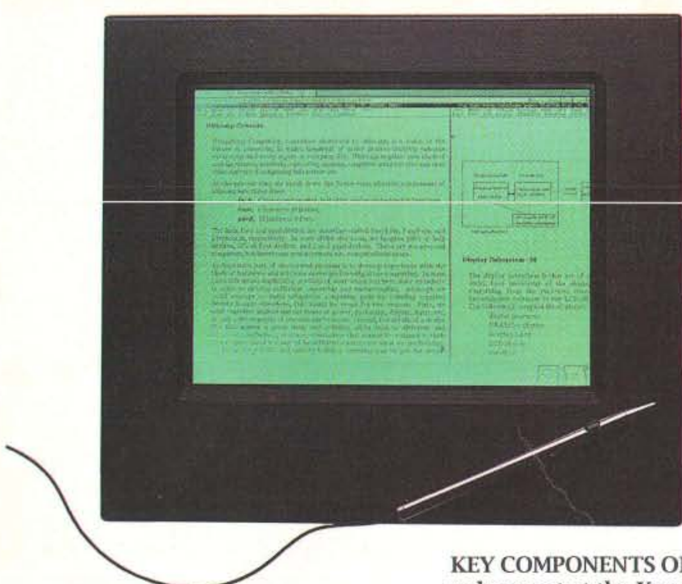
Solutions to this problem are in their infancy. Certainly no existing display system can perform well while working with the full diversity of input and output forms required by embodied virtuality. Making pads, tabs and boards work together seamlessly will require changes in the kinds of protocols by which applications programs and their displayed windows communicate.

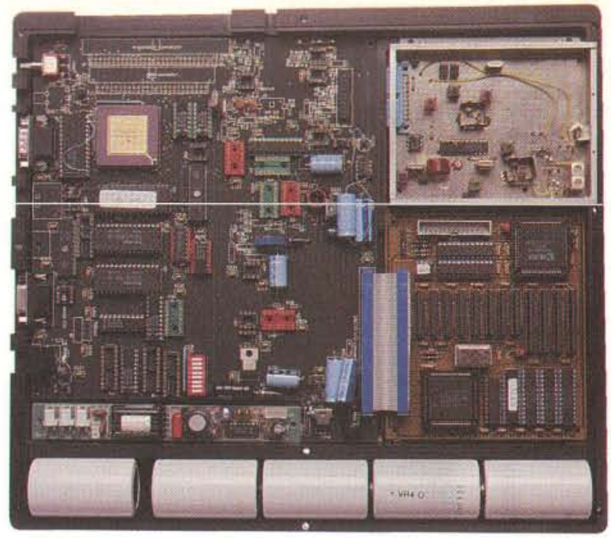


RADIO TRANSCEIVER links pads and other movable computer devices to the wired network. This unit, intended to be mounted on the ceiling, contains antennas in its crossed arms and two light-emitting diodes to signal its status.

The network that will connect ubiquitous hardware and software poses further challenges. Data transmission rates for both wired and wireless networks are increasing rapidly. Access to gigabit-per-second wired nets is already possible, although expensive, and will become progressively cheaper. (Gigabit networks will seldom devote all of their bandwidth to a single data stream; instead they will allow enormous numbers of lower-speed transmissions to proceed simultaneously.) Small wireless networks, based on digital cellular telephone principles, currently offer data rates between two and 10 megabits per second over a range of a few hundred meters. Low-power wireless networks capable of transmitting 250,000 bits per second to each station will eventually be available commercially.

Yet the problem of transparently linking wired and wireless networks resists solution. Although some stopgap methods have been developed, engineers must develop new communications protocols that explicitly recognize the concept of machines that move in physical space. Furthermore, the number of channels envisioned in most wireless network schemes is still





KEY COMPONENTS OF UBIQUITOUS COMPUTING are the pads and tabs under development at the Xerox Palo Alto Research Center. The page-size pad (*top, exterior and interior views*) contains two microprocessors, four million bytes of random-access memory, a high-speed radio link, a high-resolution pen interface and a black-and-white display that is 1,024 by 768 pixels. Because it uses standard window system software, the pad can communicate with most workstations. The much smaller tab (*at left*), $2^3/_4$ by $3^1/_4$ inches, has three control buttons, a pen interface, audio and an infrared link for communicating throughout a room. The author believes future homes and offices will contain hundreds of these tiny computers.

very small, and the range large (50 to 100 meters), so that the total number of mobile devices is severely limited. The ability of such a system to support hundreds of machines in every room is out of the question. Single-room networks based on infrared or newer electromagnetic technologies have enough channel capacity for ubiquitous computers, but they can work only indoors.

Present technologies would require a mobile device to have three different network connections: tiny-range wireless, long-range wireless and very high speed wired. A single kind of network connection that can somehow serve all three functions has yet to be invented.

Neither an explication of the principles of ubiquitous computing nor a list of the technologies involved really gives a sense of what it would be like to live in a world full of invisible widgets. Extrapolating from today's rudimentary fragments of embodied virtuality is like trying to predict the publication of *Finnegans Wake* shortly after having inscribed the first clay tablets. Nevertheless, the effort is probably worthwhile:

Sal awakens; she smells coffee. A few minutes ago her alarm clock, alerted by her restless rolling before waking, had quietly asked, "Coffee?" and she had mumbled, "Yes." "Yes" and "no" are the only words it knows.

Sal looks out her windows at her neighborhood. Sunlight and a fence are visible through one, and through others she sees electronic trails that have been kept for her of neighbors coming and going during the early morning. Privacy conventions and practical data rates prevent displaying video footage, but time markers and electronic tracks on the neighborhood map let Sal feel cozy in her street.

Glancing at the windows to her kids' rooms, she can see that they got up 15 and 20 minutes ago and are already in the kitchen. Noticing that she is up, they start making more noise.

At breakfast Sal reads the news. She still prefers the paper form, as do most people. She spots an interesting quote from a columnist in the business section. She wipes her pen over the newspaper's name, date, section and page number and then circles the quote. The pen sends a message to the paper, which transmits the quote to her office.

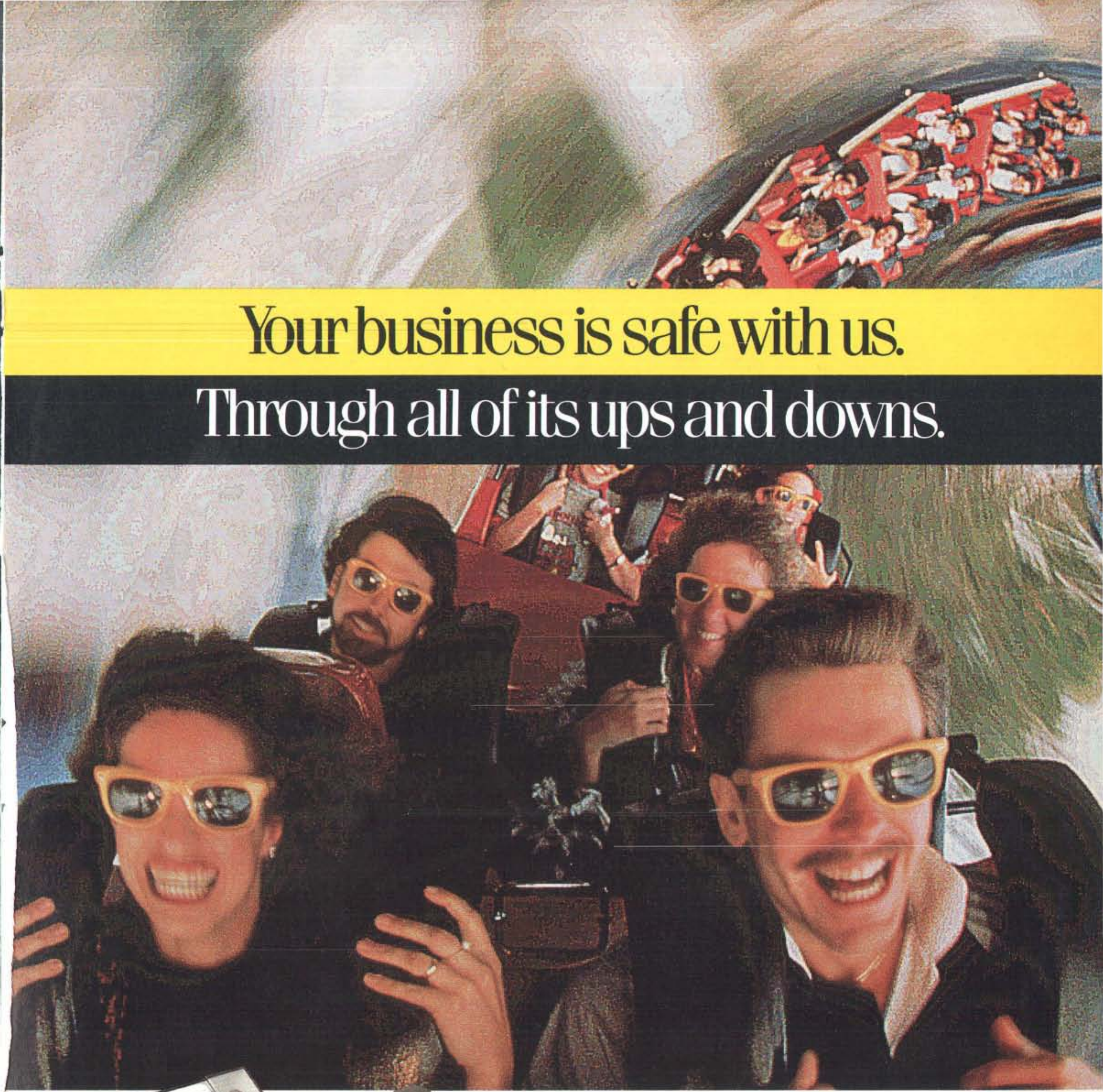
Electronic mail arrives from the company that made her garage door opener. She had lost the instruction manual and asked them for help. They have sent her a new manual and also something unexpected—a way to find the old one. According to the note, she can press a code into the opener and the missing manual will find itself. In the garage, she tracks a beeping noise to where the oil-stained manual had fallen behind some boxes. Sure enough, there is the tiny tab the manufacturer had affixed in the cover to try to avoid E-mail requests like her own.

On the way to work Sal glances in the foreview mirror to check the traffic. She spots a slowdown ahead and also notices on a side street the telltale green in the foreview of a food shop, and a new one at that. She decides to take the next exit and get a cup of coffee while avoiding the jam.

Once Sal arrives at work, the foreview helps her find a parking spot quickly. As she walks into the building, the machines in her office prepare to log her in but do not complete the sequence until she actually enters her office. On her way, she stops by the offices of four or five colleagues to exchange greetings and news.

Sal glances out her windows: a gray day in Silicon Valley, 75 percent humidity and 40 percent chance of afternoon showers; meanwhile it has been a quiet morning at the East Coast office. Usually the activity indicator shows at least one spontaneous, urgent meeting by now. She chooses not to shift the window on the home office back three hours—too much chance of being caught by surprise. But she knows others who do, usually people who never get a call from the East but just want to feel involved.

The telltale by the door that Sal pro-



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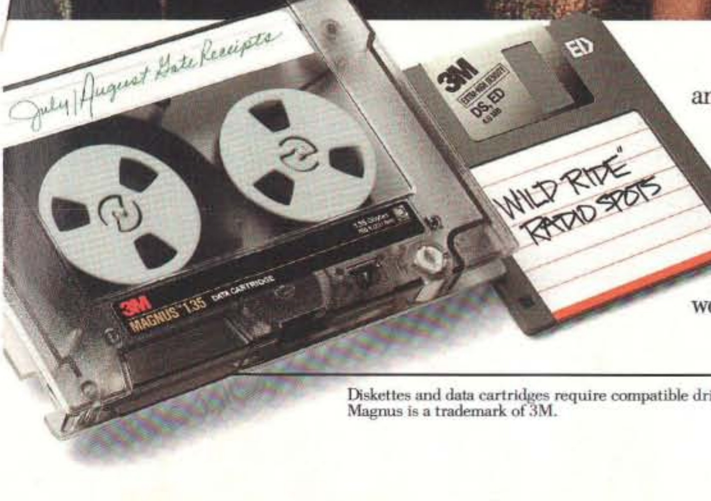

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grammed her first day on the job is blinking: fresh coffee. She heads for the coffee machine.

Coming back to her office, Sal picks up a tab and "waves" it to her friend Joe in the design group, with whom she has a joint assignment. They are sharing a virtual office for a few weeks. The sharing can take many forms—in this case, the two have given each other access to their location detectors and to each other's screen contents and location. Sal chooses to keep miniature versions of all Joe's tabs and pads in view and three-dimensionally correct in a little suite of tabs in the back corner of her desk. She can't see what anything says, but she feels more in touch with his work when noticing the displays change out of the corner of her eye, and she can easily enlarge anything if necessary.

A blank tab on Sal's desk beeps and displays the word "Joe" on it. She picks it up and gestures with it toward her live board. Joe wants to discuss a document with her, and now it shows up on the wall as she hears Joe's voice:

"I've been wrestling with this third paragraph all morning, and it still has the wrong tone. Would you mind reading it?"

Sitting back and reading the paragraph, Sal wants to point to a word. She gestures again with the "Joe" tab onto a nearby pad and then uses the stylus to circle the word she wants:

"I think it's this term 'ubiquitous.' It's just not in common enough use and makes the whole passage sound a little formal. Can we rephrase the sentence to get rid of it?"

"I'll try that. Say, by the way, Sal, did you ever hear from Mary Hausdorf?"

"No. Who's that?"

"You remember. She was at the meeting last week. She told me she was going to get in touch with you."

Sal doesn't remember Mary, but she does vaguely remember the meeting. She quickly starts a search for meetings held during the past two weeks with more than six people not previously in meetings with her and finds the one. The attendees' names pop up, and she sees Mary.

As is common in meetings, Mary made some biographical information about herself available to the other attendees, and Sal sees some common background. She'll just send Mary a note and see what's up. Sal is glad Mary did not make the biography available only during the time of the meeting, as many people do....

In addition to showing some of the ways that computers can enter invisibly into people's lives, this scenario points up some of the social issues that embodied virtuality will engender. Perhaps key among them is privacy: hundreds of computers in every room, all capable of sensing people near them and linked by high-speed networks, have the potential to make totalitarianism up to now seem like sheerest anarchy. Just as a workstation on a local-area network can be programmed to intercept messages meant for others, a single rogue tab in a room could potentially record everything that happened there.

Even today the active badges and self-writing appointment diaries that offer all kinds of convenience could be a source of real harm in the wrong hands. Not only corporate superiors or underlings but also overzealous government officials and even marketing firms could make unpleasant use of the same information that makes invisible computers so convenient.

Fortunately, cryptographic techniques already exist to secure messages from one ubiquitous computer to another and to safeguard private information stored in networked systems. If designed into systems from the outset, these techniques can ensure that private data do not become public. A well-implemented version of ubiquitous computing could even afford better privacy protection than exists today.

By pushing computers into the background, embodied virtuality will make individuals more aware of the people on the other ends of their computer links. This development may reverse the unhealthy centripetal forces that conventional personal computers have introduced into life and the workplace.

Even today, people holed up in windowless offices before glowing computer screens may not see their fellows for the better part of each day. And in virtual reality, the outside world and all its inhabitants effectively cease to exist. Ubiquitous computers, in contrast, reside in the human world and pose no barrier to personal interactions. If anything, the transparent connections that they offer between different locations and times may tend to bring communities closer together.

My colleagues and I at PARC believe that what we call ubiquitous computing will gradually emerge as the dominant mode of computer access over the next 20 years. Like the personal computer, ubiquitous computing will produce nothing fundamentally new, but by making everything faster and easier to do, with less strain and fewer mental gymnastics, it will transform what is apparently possible. Desktop publishing, for example, is essentially no different from computer typesetting, which dates back to the mid-1960s. But ease of use makes an enormous difference.

When almost every object either contains a computer or can have a tab attached to it, obtaining information will be trivial: "Who made that dress? Are there any more in the store? What was the name of the designer of that suit I liked last week?" The computing environment knows the suit you looked at for a long time last week because it knows both of your locations, and it can retroactively find the designer's name even though that information did not interest you at the time.

Sociologically, ubiquitous computing may mean the decline of the computer addict. In the 1910s and 1920s many people "hacked" on crystal sets to take advantage of the new high-tech world of radio. Now crystal-and-cat's-whisker receivers are rare because high-quality radios are ubiquitous. In addition, embodied virtuality will bring computers to the presidents of industries and countries for nearly the first time. Computer access will penetrate all groups in society.

Most important, ubiquitous computers will help overcome the problem of information overload. There is more information available at our fingertips during a walk in the woods than in any computer system, yet people find a walk among trees relaxing and computers frustrating. Machines that fit the human environment instead of forcing humans to enter theirs will make using a computer as refreshing as taking a walk in the woods.

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Products and Services for Computer Networks

Tired of the constraints of space and time? Intelligently designed network products that understand the needs of individuals will set us free

by Nicholas P. Negroponte

During a dinner party, you might wink across the table at a close friend. By applying a slightly perverted measure of bandwidth, we can claim that your wink delivers a mere one bit. Yet that bit carries an enormous amount of information; if asked, you might need more than 100,000 bits to explain the content of the message to a stranger. In a real sense, you achieved data compression in excess of 100,000 to one. With that degree of compression, we could send high-definition television (HDTV) over telephone lines at the sluggish rate of only 1,200 baud (bits per second).

The success of the wink cannot be understood through the normal study of network efficiency. When sizing up networks, we tend to look at their channel capacity, without due consideration of the computational abilities of the transceivers. The wink works for a contrary reason: the transmitter and the receiver share a body of common knowledge and experiences, and they have the intelligence to put the act of winking into context. At the moment, we are devoting almost no effort to building networks with similar cunning.

If we are looking for creative applications of future networks, then we cannot isolate thoughts about channel mode and capacity—flat estimates of how much information can travel how fast—from the computational resources at the ends of the network. The propositions supporting that truth seem counterintuitive to some people; indeed, many of my colleagues do not yet accept them. Nevertheless, to prove my point, I will look at the relevance of this truth to three domains of products and services: entertainment, transactions and electronic personal surrogates.

First, however, let us debunk bandwidth. Many networking professionals argue that networks will be useless without the broad bandwidths made possible by optical fiber lines. They say that we must push to replace copper wires with fiber; only then can we have broadband networks capable of sending data at sufficiently high speeds.

Yet, ironically, broadband systems are inevitable. The cost and maintenance for fiber lines will be so much less than for copper ones that fiber will be installed even without the need to accommodate wideband services. The rush to justify gigabit services is merely a historical anomaly; today is a time of crossover between the falling cost of fiber and the generally steady cost of copper. The installed base of fiber will grow no matter what new services we offer. The problem is that its natural growth is too slow for those who can imagine the benefits of bandwidth—or who might profit from them.

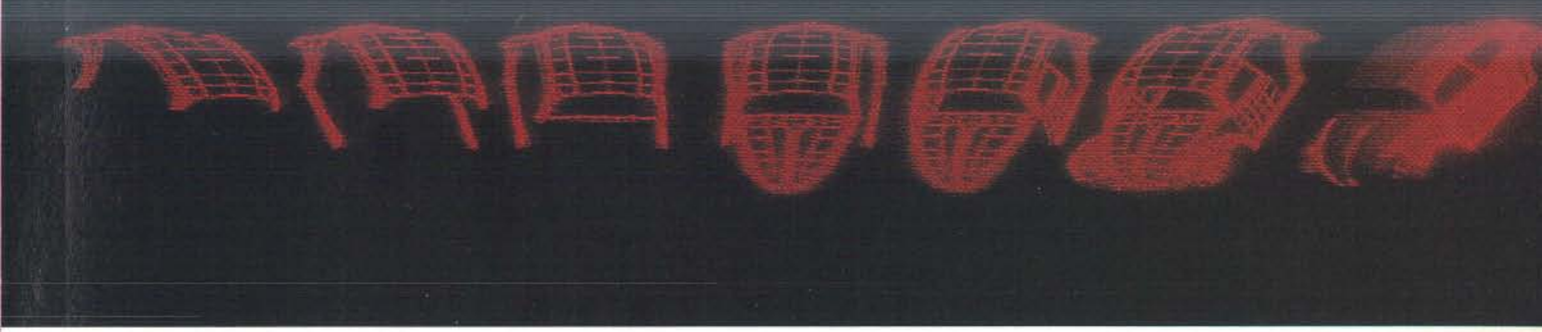
By trying needlessly to justify the inevitable, many network products and services being proposed now are contrived or, worse, made with total disregard for concurrent advances in computing. People with a vested interest in the network are saying that we need big data pipes connecting our machines because we will be naive about how to process and store information. One such claim, for example, is that we will need broadband networks to transmit video. In fact, we already know that video can be delivered over the T1 (1.5-megabit-per-second) twisted-pair copper wires existing today. The real products and services of the future will come from imaginative applications of both channel and computing capacity, not from either alone.

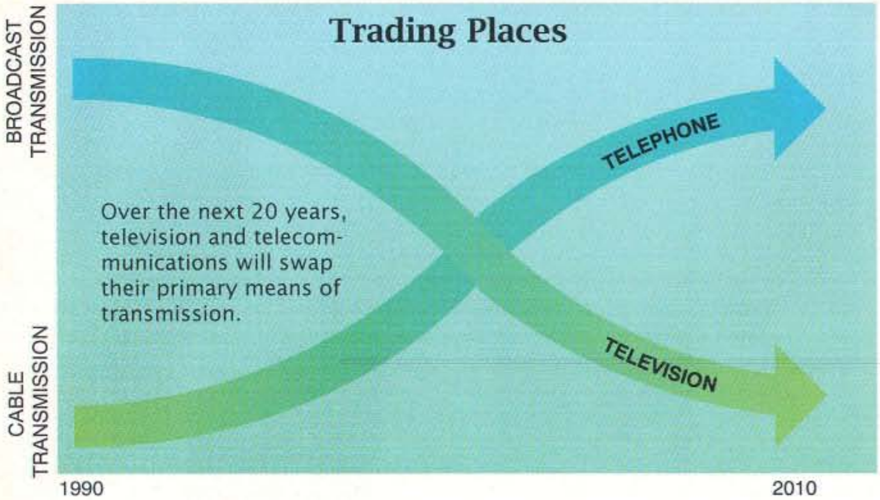
Postmodern man is potentially a nomad. An educated guess is that the authors in this issue of *Scientific American* spend on average more than half of their time traveling. According to one theory, if we had good teleconferencing and extraordinarily easy to use broadband services, most travel would be unnecessary—we could all stay home, preserve the ozone layer from jet exhausts and avoid the wear and tear on our bodies. Yet staying at home would not be the most interesting consequence of better networks.

The often overlooked point is that we can freely move about precisely because we have the electronic means to stay in touch with our home base. No one needs to be more than a telephone call, data transfer or fax transmission away from the office—indeed, from any office. What we network planners should be looking at is not the bits per second required to lower our frequent-

NICHOLAS P. NEGROPONTE is the founder and director of the Media Laboratory of the Massachusetts Institute of Technology, where he is also professor of media technology. He has written and lectured extensively about the promise of computer technology, human-machine interfaces and the changing nature of communication. Negroponte studied architecture at M.I.T., receiving his master's degree in 1966. Within a year he had founded the Architecture Machine Group at the same institution. He has been a visiting professor at the University of Michigan, the University of California at Berkeley and Yale University.

MOVING HOLOGRAMS created by computers in real time have been developed by the Media Laboratory of the Massachusetts Institute of Technology with support from the Defense Advanced Research Projects Agency and Rome Laboratory. As the technology for producing these images improves and is integrated into the information network, holograms may become important vehicles for presenting news and entertainment.





flyer mileage but the computational and telecommunications resources that will allow us to be more or less independent of space and time.

Independence of space and time is the single most valuable service and product we can provide humankind. This outcome need not translate itself into a nomadic existence, although the concept is not without interest. It can also allow us to remain in our pajamas as long as we please.

Travel embargoes during the Persian Gulf War resuscitated interest in teleconferencing, which undoubtedly will continue to gain appeal (if only by corporate fiat in response to gratuitous business traveling). The more fascinating developments, however, will come from new services that free you to wander and that create an electronic surrogate for you on the network with which others can communicate.

Those developments will of course hinge on storing and transmitting information, either through electromagnetic broadcasts or over optical fiber. Broadcast spectrum is scarce, whereas fiber, like computing power, is something we can just keep making more of. Those facts mean that the channels for distributing different types of information, as we know them today, will trade places. Most information we receive through the ether today—television, for example—will come through the ground by cable tomorrow. Conversely, most of what we now receive through the ground—such as telephone service—will come through the airwaves.

Two rules of thumb define how information should be distributed. First, use the broadcast spectrum to communicate with things that move: cars, boats, airplanes, wrist telecommunication terminals, dog collars, scuba tanks and the like. Second, deliver information to the desktop or living room by fiber.

It is already easy to see these rules in action. The popularity of cellular telephones and cable television initiated the trend, and it will not stop. Within 20 years, it will be perverse, if not illegal, to use satellites for broadcast television. The Federal Communications Commission (FCC) should put the television networks and independent stations on notice that their spectrum will slowly be withdrawn and encourage the cable operators and telephone companies to begin collaborating immediately.

Do you recall O. Henry's Christmas short story, "The Gift of the Magi," about an impoverished husband and wife? He wanted to buy a comb for her long, beautiful hair, and she wanted to buy him a gold chain for his pocket watch. She secretly cut and sold her hair to buy the chain, and he pawned his watch to purchase the comb. Something akin to this is happening with television and computers.

Television manufacturers are increasingly adding computing power to their receivers, and computer makers are putting more video into their workstations. Although this development may seem like a merger of the technologies, each side is disregarding the underlying utility of the other's techniques and aims. As a result, the television makers are cutting off their own access to the broader information delivery market, and computer manufacturers are pawning their license to be in the entertainment industry.

After considerable nationalistic fuss, the U.S. has emerged as the potential world leader in advanced television by finally opting to go digital. Europe and Japan are embarrassed by the development because they have chosen to take nondigital paths. Nevertheless, the U.S. has farther to go in its approach to HDTV because, at the moment, all the proposals to the FCC are sadly and uniquely focused on delivering better-resolution pictures. Digital television has much more to offer than higher picture resolution.

Two fundamental attitudes toward digital image transmissions in general and television in particular need to change before we will see creative thought in this area. First, we must think of images as scalable. Bigger pictures require proportionately more pixels to represent them and more information to describe them. Today both a four-inch video display and a 27-inch display use the same number of pixels, so the quality of the images changes with size.

Second, in the long run, model-based image transmission and encoding are better than transmission of pictures alone. Mathematical models of a scene can describe the spatial relations of the objects in it and maneuver them through space. The idea of capturing a picture with a camera is obsolete if one can instead capture a realistic model from which the receiver can generate any picture. For instance, from a real-time model of a baseball game, a fan watching at home could get the view from anywhere in the ballpark—including the perspective of the baseball.

The entertainment industry will be one of the first to capitalize on the new networking environment for products and services. In fact, some groundwork for expansion is already in place. Nintendo currently has an installed base in the U.S. of more than 30 million electronic game machines; they are found in more than 70 percent of all the homes with a child between the ages of eight and 12 years. In short, Nintendo is America's largest domestic computer presence and potentially the country's major force for educational change. (Seymour A. Papert of the Media Laboratory at the Massachusetts Institute of Technology is working with Nintendo to understand better what children already learn from electronic games.) On a network, these machines would change the face of our culture.

But Nintendo does not see itself as a computer maker; company executives maintain they are in the entertainment business. They are not suffering a lack of vision; everyone knows that entertainment is big business. Furthermore, it is likely to become very high tech and a major player in network products and services. Speaking more generally, as products and services continue to evolve, businesses will be more inclined to define themselves by the services they offer to customers and less by the technologies they use.

The first network entertainment ser-

vice to become available is likely to be "movies on demand" because the technology for it will be developed the soonest. How often have you walked into a video store and rented a movie that you have already seen or that turned out to be something you would never want to watch? Movie buffs rent videos brilliantly, but the rest of us are unable to remember which Clint Eastwood film we have seen or to know from its title that *Silence of the Lambs* is a chilling movie about a psychopath. The in-store classifications of drama, action, comedy, foreign and so forth are of little help.

Imagine a different scheme in which you could look at a dozen playing card-size movie trailers, or previews, on your TV screen at the same time. Scalable video makes such a plan entirely possible. By modestly interacting with your TV to indicate your choices of actors or themes, and by relying on your TV's record of what you have already seen, you could easily select the perfect film from any of the 50,000 movies made in the Western world since the inception of cinema. Indeed, it would be only slightly more difficult to ask only for a movie that is similar to another one that you liked.

The network's task would be to store movies somewhere and to deliver them to you instantly. The storage task is not outrageous. For current VHS quality, one hour of movie is about five gigabits. Although the best commercial dynamic random-access memory (DRAM) chips today can hold only 64 megabits, capacities are growing exponentially. By 2000 it should be possible to store a film on five one-gigabyte chips. Just 250,000 chips will be able to store every Western movie ever made. Until then, all 50,000 movies could be stored on twice that many compact discs (CDs) or, in the still nearer term, on 50,000 videodiscs.

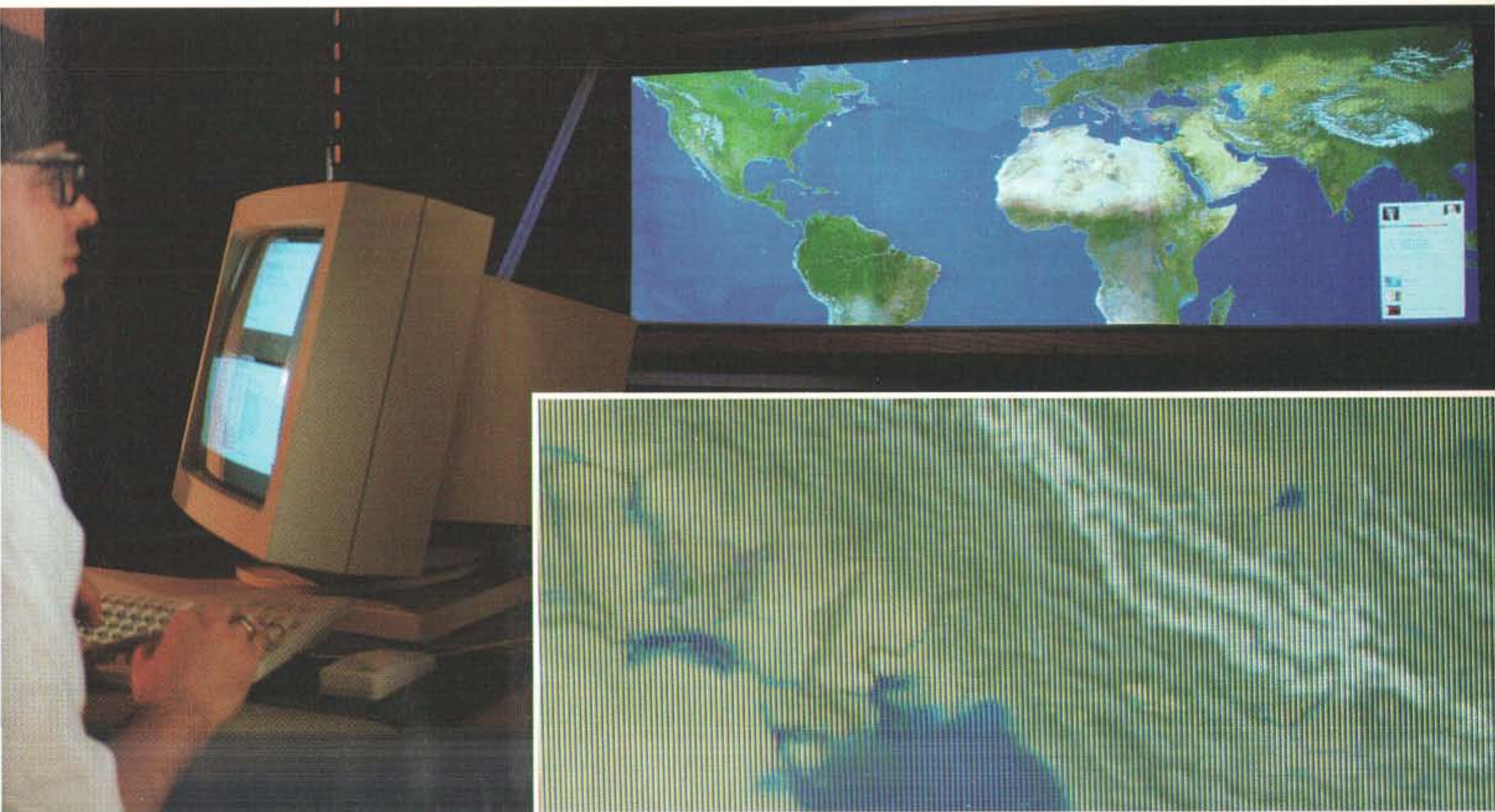
The movie-viewing customer is not the only one who would benefit from this scheme. When M.I.T.'s Media Lab was asked to investigate the technology for Columbia Pictures in 1983, the idea was to use the compact audio disc as a new form of packaged media that could be purchased for a price equal to that of rental. The idea appealed to movie companies because they could get a piece of the action for each copy sold to the public, instead of the one-time income from tapes sold to video rental stores. Today a standards organization, the Motion Pictures Expert Group, is helping to coordinate the efforts of IBM, Apple, Intel, Philips, Sony and other companies that have become interested in the development of compact-disc video.

Because a movie would be encoded only once by its marketers and decoded millions of times by viewers, considerable effort and money can be applied to ensure the quality of the encoding process. Encoding need not be done in real time. Sophisticated data compression techniques can "look ahead" through a video and find scenes rich in information (that is, rapid rates of pixel changes); some of those "excess" data can be saved along with earlier scenes that have little information. By stuffing the "peaks" into the "valleys," one can maintain consistently high data compression. In this fashion, one hour of a movie not only fits on a CD but can be pushed through the CD's narrow-band audio port.

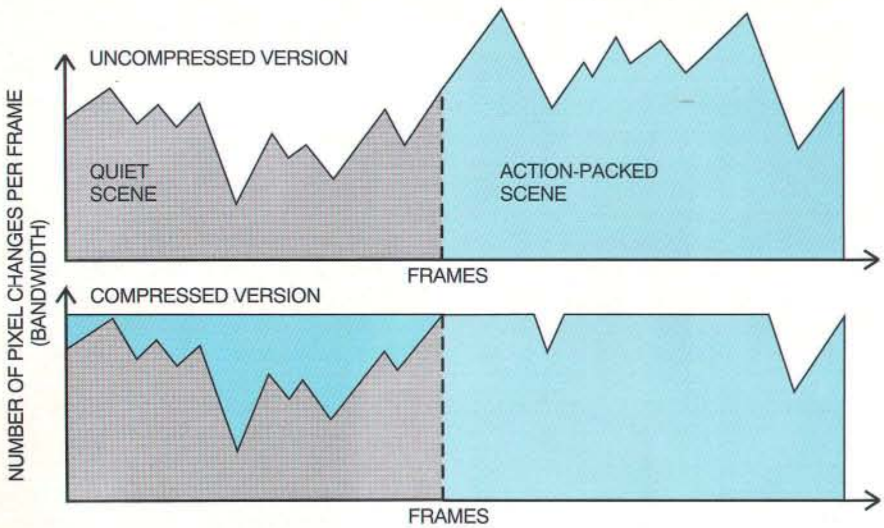
An even more interesting application of the same compression techniques is to bundle video data into efficient packets that can be transmitted rapidly. In this way, over a fiber running at a gigabit per second, one hour of video can be shipped in only five seconds. Therein lies a cogent example of how using both computer intelligence and bandwidth to deliver a service is superior to the traditional approach, which declares that video is a bandwidth hog requiring a continuous delivery stream.

In packeted form, video can be delivered to a memory-equipped receiver and viewed in an order different from

VERY HIGH DEFINITION TELEVISION being developed at the Media Lab offers almost photographic-quality images. The display has 2,000 vertical lines of resolution, compared with the 480 lines for standard television. Only in extreme close-up does a detail of the Persian Gulf (*inset*) begin to exhibit the poor quality seen on current television sets. The 6,000-pixel width of the display is achieved by tiling three 2,000-pixel monitors side by side.



"Look Ahead" Video Compression



"Look ahead" video compression is a technique that makes it possible to encode and transmit recorded video information efficiently. Prior to compression, the levels of information change greatly from frame to frame (*top*). This technique reduces the bandwidth required to deliver the signal by fitting the "peaks" into the "valleys" (*bottom*). After additional compression techniques are performed, one hour of video can be transmitted over a fiber in less than five seconds.

that in which it was sent. Related packets would not be sent sequentially but would be interlinked or indexed by content. Viewers could navigate up or down through this hierarchy of information. Someone watching a television news program, for instance, could push the "tell me more" button on the TV, and Dan Rather would elaborate on a particular story to various levels of depth—all the while providing substance that would otherwise have been relegated to the cutting-room floor.

Although television need not be a bit guzzler, holographic video is another story. Fifteen years ago in *Star Wars*, many of us saw R2D2 beam Princess Leia's three-dimensional image onto Obi-Wan Kenobi's floor. Cinematic special effects aside, real-time holography will not appear in living rooms for a few decades. The Media Lab, which is to my knowledge the only laboratory working on real-time holography, has achieved it for images measuring about one cubic inch. Those images are achieved with a massively parallel, multimillion-dollar computer, a roomful of electro-optic instruments, a spinning mirror and a heavy-duty laser. It is unclear how that technology will scale up to allow eight-inch-high football players to run around your house passing a half-inch football.

Look at the numbers. The Media Lab's current system uses a 50-megabit-per-second channel to generate a small image. Scaling up to a living room–size football game would require computing 45 terabits per second by brute force. Even if we subtract three orders of magnitude by using "smart" processing techniques, we are still looking at 45 gigabits per second.

The massive bandwidth consumption of holography suggests that it will be necessary for a receiver to get a computational model of an event rather than raw holographic data. The holographic images for the living-room football game could be generated from an accurate model. Information for manipulating that model would be sent over a fiber, but the image would actually be computed and created by the receiver—not captured by a camera.

Regardless of whether the model or the hologram is transmitted, substantial bandwidth is required—the bandwidth that only fiber can deliver. Although my football example is drawn from the world of entertainment, it is likely that the technology will first be developed in medical imaging for remote diagnosis in the near term and teleoperations in the longer term.

Information has value, but it is as perishable as fresh fruit. It varies from person to person, from moment to moment. And in some cases, the value can suddenly drop to zero: the knowledge that a seat on an airplane is empty becomes worthless when the plane pulls away from the jet way. But when information leads to a transaction, such as a booking for that empty seat, the value is less ephemeral. A service that facilitates transactions earns the gratitude of both the buyer and the seller. The service, in turn, is equally happy because it can probably bill both parties. Information transactions have so much appeal for both businesses and consumers that they are sure to be among the first network products and services.

Multimedia computing, which combines moving video, audio and text, is likely to be an important tool for transactions. It is anticipated to be a serious bandwidth consumer, but short-term multimedia solutions need not be. Customers at home could access some information at a remote site by narrowband communications. The rest could already reside in the home at the time of the transaction, having arrived there by regular mail or overnight delivery. (If you send three CDs by Federal Express Priority One service from Los Angeles to Boston, then the information transfer is greater than a modern 64-kilobit-per-second data line could provide during the same time.)

A simple example would be the use of a videodisc for summer-home rentals. As many as 54,000 houses could be pictured on the disc, which could be distributed to potential renters. Users would control the disc by specifying what they wanted in a summer house: the cost, the number of rooms, the seasonal availability, the location and views, and so on. The viewing system would display only the available houses that fit the criteria. In this case, videodisc technology created a product, but the network mixed the central and local computing services to make the transaction possible.

More generally, the problem and solution can be described as a kind of Yellow Pages. In this context, however, the term has several meanings that go beyond those you might associate with this venerable publication. For example, electronic Yellow Pages could be geographically coded so that a company or service could be related to who you are, where you are, where you are going and what might be along the way. Because this Yellow Pages would be an active part of the network rather than a static book on a shelf, it could contain up-to-the-minute information about its advertisers. It could include, for example, tonight's specials at your favorite restaurant or today's bargains at Bloomingdale's.

More than 95 percent of the services that advertise in the Yellow Pages use them as their only advertising. For that reason, the opportunity for adding layers of detail, daily information, photo-

graphs, video pitches and audio narratives will appeal to service providers. The customer would also welcome that information. The data base could be explored from totally original angles, such as "Who is serving fresh white truffles tonight?" Transactions that result from those queries are more like making a date than buying yogurt.

The opportunity is made-to-order for multimedia network products and services. Yet, it will require Federal Judge Harold Greene to relax some of his restrictions on the telephone companies that bar them from getting into the information-providing business. Simultaneously, the current information providers, particularly newspapers, will have to become more aggressive and imaginative in the electronic milieu.

Today print advertising falls into roughly three groups: persuasion by affiliation, convincing with facts and selling the specific. By affiliating their products with yachts, cowboys and good-looking people, cigarette and liquor ads are archetypes of the first category. Automobile and department store ads are an example of the second. The classified section of the newspaper embodies the third. In every case, the reader must more or less stumble on the relevant information: it does not percolate to the top of the information strata when the reader enters the market for a car or a summer suit.

The big change for print media is that advertising will become news and that persuasion by affiliation will die off. The network will be sufficiently personalized to anticipate your needs and interests and smart enough to find obscure auctions of fly-fishing equipment in the dead of winter. Advertisers will not necessarily be unhappy with such a network, because the broad reach is narrowed to a few who have a likely interest. Imagine how delighted General Motors and Nissan would be to have the opportunity to advertise to you specifically when you start looking for a new BMW.

Almost all services can distinguish themselves by becoming personalized. We are pleased to be recognized and catered to as individuals rather than being treated as a faceless part of the mob. Personal information systems, like the wink, are also extremely efficient. In this regard, the most desirable interaction with a network is one in which the network itself is invisible and unnoticeable. Planners often forget that people do not want to use systems at all—easy or not. What people want is to delegate a task and not worry about how it is done.

Calling someone on the telephone is an excellent example: the physical design of the handset, the brightness of the displays and the feel of the buttons should be utterly irrelevant. The caller simply wants to direct the telephone to contact so-and-so and to do something appropriate if that person is not available. Finding the person (or failing to do so) is only a part of the task; doing the appropriate thing is what matters and takes extraordinary personalization and intelligence.

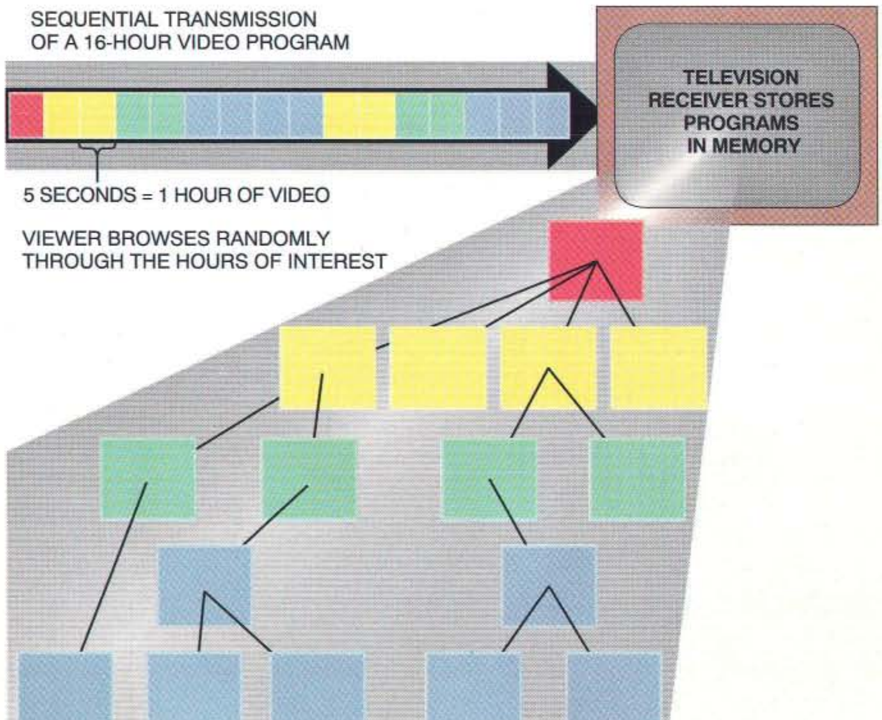
What constitutes knowing someone? Usually it is a shared body of knowledge, but not in the sense of two people knowing organic chemistry. Rather it is in the sense of two people sharing experiences. Each of us has a sphere of acquaintances, professional and personal, with whom we work and play. Similarly, we each have our own habits, patterns of life and idiosyncracies. Our jobs involve networks of people who assume different degrees of importance in our lives at different times. We know them because we are familiar with their ways, and they with ours.

What makes a system personal is its knowledge of such information. In a very real sense, the system becomes a bona fide member of your personal and professional community. Electronic personalization is by definition a mix of centralized and decentralized information, manipulated and filtered by a retinue of electronic agents.

A personalized newspaper serves as a good example. What would you want in such a newspaper? The question is tricky because, on the one hand, you would like stories that interest you. On the other hand, you would not entrust to any human or machine the wholesale dismissal of all other information. You might not normally be interested in news of a sporting event, but you know that your attitude would change if a close friend were competing. Newsworthiness is in the eye of the beholder—and not just the eye of the editor. Yet to date, the beholder has not been a part of the equation, except by coarse selection of one newspaper or magazine over another.

In the future, news and personal information systems will have the potential to be much more integrated than they are today, which should be highly beneficial. If your early-morning flight is delayed, that fact should appear as the lead headline in your personalized newspaper. Indeed, if the network is

"Tell Me More" Television



Packets of transmitted video information, all constituting one program, can be sent to a memory-equipped television receiver. The viewer can then browse through any of these hours of information in any order, seeking elaborations on subjects of interest or skipping what seems irrelevant. In this way, watching television can become more like reading a book or having a conversation.

smart enough, it should tell your alarm clock to let you sleep an additional hour (after checking for other airline routing options). And if your flight is on schedule, you should expect your morning edition to include the weather report for the city of your destination (so that you leave town with an umbrella in spite of the blue sky).

Some people cry at this point, "Tilt! I don't want my newspaper to be so personalized!" The arguments against the idea are usually twofold: "I count on the impersonal newspaper to be a common subject for conversation, and I assume other people know this as well," and "I don't want to become narcissistic and introverted by hearing only what I want to hear all the time."

These concerns are not totally misguided. Still, they assume that personalization is a full swing away from common knowledge, which it need not be. In fact, if you think of your best friends, they are people who do not tell you what you want to hear but are willing to tell you what they believe to be the truth and what is in your best interest. Such could be the case with an electronic agent as well; it need not be limited to what it thinks you want to know. The trick is timeliness. Our elasticity for less relevant information is very different on early Monday morning than it is on Sunday afternoon or when sitting in a garden compared with stepping over the threshold into an important meeting.

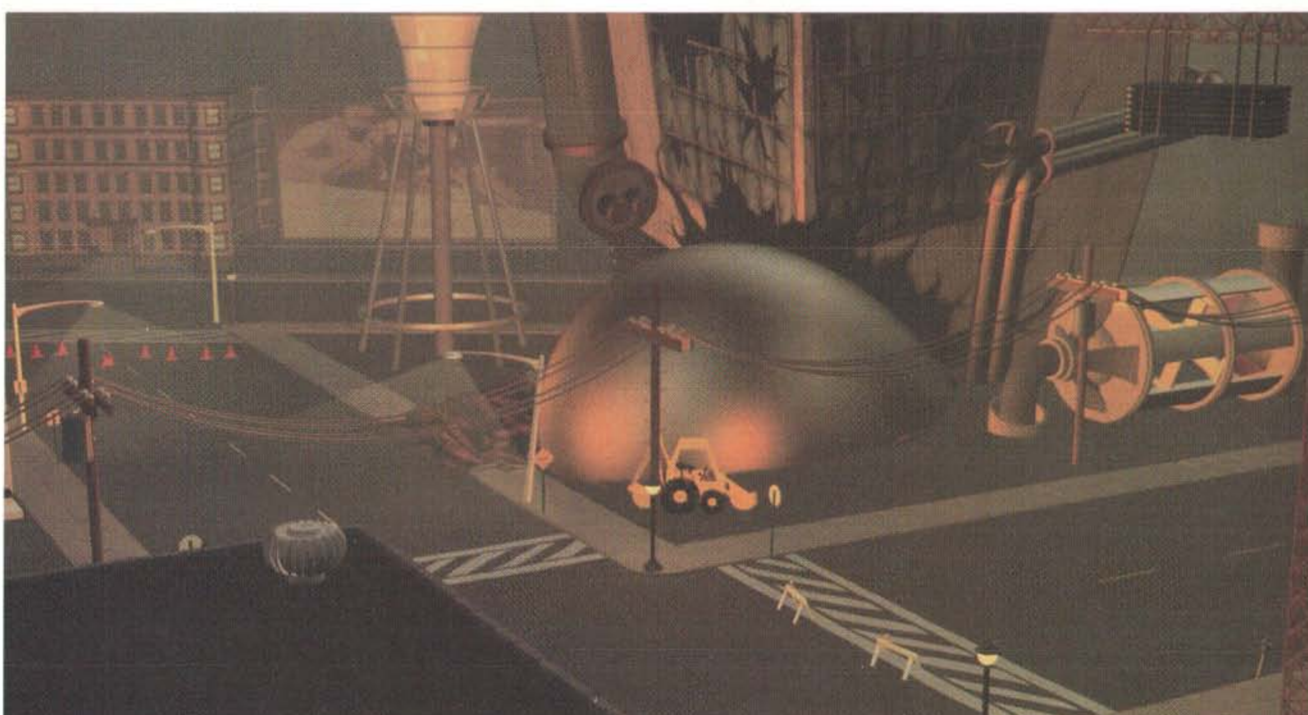
Consider personalization in the context of a telephone, which today rings indiscriminately. A well-trained, experienced butler will respond to a call on the basis of who is calling and, in many cases, of what the caller wishes to say. While this arrangement may sound one-sided, it is not. Often, the caller is delighted to get the butler and leave the message regardless of whether the intended recipient is there, just to ensure the timeliness of the message's delivery. The network of the future should behave no less intelligently.

A specific example of personalizing information can be found in the idea of individualizing television. The example is interesting in that it individualizes the premiere mass medium and, in some ways, turns the idea of television networks upside down.

In 1965 the Carnegie Corporation asked James R. Killian, Jr., former president of M.I.T., to chair a commission on educational television that laid the foundation for the Public Broadcasting System. As the commission approached the end of its work in 1967, the need for a more technical view of the future surfaced; J.C.R. Licklider of M.I.T., who was famous for his work on computer and human interfaces, was asked to provide a quick appendix. In it he coined the term "narrowcasting." He wisely foresaw an emerging need to make more specialized programs that would appeal to smaller audiences. That idea has been taken up enthusiastically by the magazine industry in particular and by the information distribution industry in general: they are doing more and more narrowcasting of all kinds. What Licklider missed was the once unthinkable limiting case: the audience of one.

Contrasting broadcasting with narrowcasting overemphasizes the difference between "broad" and "narrow." Instead we should be focusing on the word "cast." Stewart Brand, in his book *The Media Lab,* coined a term, "broadcatching," that draws attention rightly to the real challenge: to catch television and other media information selectively so that the sum of the collected parts is personalized.

As mentioned earlier, it is possible to transmit one hour of TV in five seconds. In principle, your television could look at more than 5,000 hours of programming during a seven-hour workday. One can imagine a system of television indexing. In the near future, programs could be digitally broadcast with a table of contents at the beginning. By consulting this table of contents, your intelligent TV set could filter out inappro-



THIS FRAME OF ANIMATION for high-definition television would require about 50 million bits to describe all the pixels; 30 frames per second are needed for animation. Transmitting that much information fast enough would take enormous bandwidth. If a computer in the receiver holds models of the pictured objects, however, only instructions about their movements need be sent. Smoothly moving high-resolution images are therefore possible with low bandwidths.

priate programs. It could then more or less edit the 5,000 hours of programming it has monitored into a short, distilled collage lasting no more than, say, 10 minutes. Elaborations on the contained subjects of interest could be obtained by instructing the TV to "tell me more." The total length of the stored programming would be limited only by the receiver's memory capacity. Broadcatching of this sort can be generalized to many media. The personalized aspect of the provided service would be handled by the receiver, not by the network as a whole.

Too often networks are likened to highways. By analogy, we are going from a system of country roads to one of autobahns, with wider lanes and higher (or no) speed limits. This comparison is misleading because it suggests that the network can stand by itself. That is not the case. The added intelligence at each node and at the ends of the network are what make the system work.

To understand the difference that intelligence makes, think about how printed information can be distributed electronically. A book could be stored in one location and shipped anywhere as a facsimile in no time at all. Each page would be fully encoded as a bit-map illustration, a faithful reproduction of the page, like a picture of it. At first glance, that prospect is tantalizing, especially to those of us who have suffered through 40- or 80-character columns of text while knowing that the printed originals had a rich, expressive and readable format. Yet on closer examination, storing and transmitting books as faxes is a dreadful mistake.

The right way to solve the problem is to store a description of a page format, including the typographics in which text is printed. That page description should be transmitted along with the ASCII code for the characters in the text and the bit-map information for the photographs and other structured graphics. At the receiving end, one needs the computer intelligence to decode the page description language and display the "pages" of the book.

Why is this approach so desirable? Two reasons. For one, the information in the book remains computer readable. Machines can refer to the text and decide whether to retrieve, route or file it. For another, in this form the information can be reformatted for display on a variety of media: you may occasionally want the information delivered to a display on your wrist or in your vest pocket rather than getting a facsimile of the original page.

PERSONALIZED ELECTRONIC NEWSPAPER can be compiled by computers scanning the network for information of particular relevance to specific individuals. A sophisticated electronic model of a person can be used to determine which news items should be selected and how much prominence and detail they should have.

Mind you, the mistake of facsimile is not limited to those people bent on finding excuses to consume bandwidth or promulgate dumb terminals. It is evident today in all our daily lives. The notion of "imaging" documents in general and the presence of fax machines in particular are setting back by decades the cause of making information more readable to computers.

Just think of how this inefficiency is part of your own behavior. You type a letter on a word processor, print it on a laser printer and stuff the hard copy into a fax (or use a fax modem). The last step in this chain just deleted the computer-readable format of the text; the recipient can no longer use the text in an information management system that would have access to the content. Yet we all do this because there are many more fax machines than coherent electronic mail systems (let alone systems capable of interpreting page description languages).

The fax, a dumb terminal par excellence, perfectly represents the services that result when we do not focus on the intelligence of the network and its ends but instead rely on the lowest common denominator of transceiver. Making such mistakes grossly limits the quality and originality of the products and services that can later arise. Let us not make them again with broadband networks; networks present real opportunities for liberating us that are much too enticing to forfeit.

FURTHER READING

THE HUMAN INTERFACE: WHERE PEOPLE AND COMPUTERS MEET. Richard A. Bolt. Van Nostrand Reinhold, 1984.

THE ART OF HUMAN-COMPUTER INTERFACE DESIGN. Edited by Brenda Laurel. Addison-Wesley Publishing, 1990.

INTO THE TELECOSM. George Gilder in *Harvard Business Review*, Vol. 69, No. 2, pages 150–161; March/April 1991.

SWATCH TELECOM PRODUCTS: *Taking the confusion out of communication*

Why would Swatch, the company often credited with virtually saving the Swiss watch industry single-handedly, turn to telecom? What advantage does its parent, SMH — "Swiss Corporation for Microelectronics and Watchmaking Industries" — see in designing, engineering and marketing telephones and other telecom products?

Jürg Schär, Swatch's president: "The revolution that has hit the European PTTs, and others, opens the market to consumer-oriented brands like ours. We are driven by the tastes and needs of the end-user, unlike technology-driven companies whose products too often end up all bells and whistles — excellent in the conception to be sure, but intimidating to the public." So Swatch introduced the Twinphone, first in the US (late 1988), a year later in Switzerland and Japan, and then in Italy, the UK and smaller markets. Its technology: state-of-the-art, but with a Swatch twist — fantastic design, easy access, meant to be fun to use. The standard Twinphone allows one party to use the base, another the receiver — thus "twin." Its deluxe model offers instant access to twenty numbers just by punching in the first three letters of a real name. Its "alpha-numeric automatic memory recall" sounds complex. But Swatch Telecom makes it simple. The phones reach market through Swatch's own wholesale distribution network; at retail, you find the product in high-end electronics shops and department stores. And a redoubtable network it is: the company last year moved 13 million watches onto wrists worldwide.

"It is not enough to make a product and put your name on it and assume people will respond," says Schär. "They need to be educated to Swatch as a telecom source ... and people have to have choice." Just over the horizon? Later this year (first in the US and Italy), a Twinphone with a built-in answering device. Next, a pager-watch. "This called for re-design of the Swatch," explains Tuomo Lähdesmäki, General Manager / Swatch Telecommunications, "and was engineered in-house at the SMH Group's ETA division, using the advanced low-power technology of our EM Marin Microelectronic unit. The pager's four-tone system lets the user identify the caller." The pager's price:

swatch

A company of SMH

a very marketable 250 Swiss francs, under $170. Next: a pager-in-the-(analog) watch with a numeric display of the number the owner-wearer should call.

Consider that no one has put such features so compactly into a watch, rendered everything essentially invisible; even the antenna is completely integrated. Users subscribe with their local phone company. Again, Swatch makes it easy: and thus the sign-up is effected at the point-of-sale.

Schär: "We are working on a cordless phone specifically for the US market. Again, it will have the uniquely Swatch characteristics: easy to understand and use, aggressively priced, reaching the market through selective distribution and offering special styling. Here, as always, we are oriented to the individual end-user, not business users. It is also a question of life-style. People are not such 'tech freaks' as they were." ◆

Computers, Networks and Work

Electronic interactions differ significantly from face-to-face exchanges. As a result, computer networks will profoundly affect the structure of organizations and the conduct of work

by Lee Sproull and Sara Kiesler

Although the world may be evolving into a global village, most people still lead local lives at work. They spend the majority of their time in one physical location and talk predominantly to their immediate coworkers, clients and customers. They participate in only a few workplace groups: their primary work group, perhaps a committee or task force and possibly an informal social group.

Some people, however, already experience a far more cosmopolitan future because they work in organizations that have extensive computer networks. Such individuals can communicate with people around the world as easily as they talk with someone in the next office. They can hold involved group discussions about company policy, new product design, hiring plans or last night's ball game without ever meeting other group members.

The networked organization differs from the conventional workplace with respect to both time and space. Computer-based communication is extremely fast in comparison with telephone or postal services, denigrated as "snail mail" by electronic mail converts. People can send a message to the other side of the globe in minutes; each message can be directed to one person or to many people. Networks can also essentially make time stand still. Electronic messages can be held indefinitely in computer memory. People can read or reread their messages at any time, copy them, change them or forward them.

Managers are often attracted to networks by the promise of faster communication and greater efficiency. In our view, the real potential of network communication has less to do with such matters than with influencing the overall work environment and the capabilities of employees. Managers can use networks to foster new kinds of task structures and reporting relationships. They can use networks to change the conventional patterns of who talks to whom and who knows what.

The capabilities that accompany networks raise significant questions for managers and for social scientists studying work organizations. Can people really work closely with one another when their only contact is through a computer? If employees interact through telecommuting, teleconferencing and electronic group discussions, what holds the organization together? Networking permits almost unlimited access to data and to other people. Where will management draw the line on freedom of access? What will the organization of the future look like?

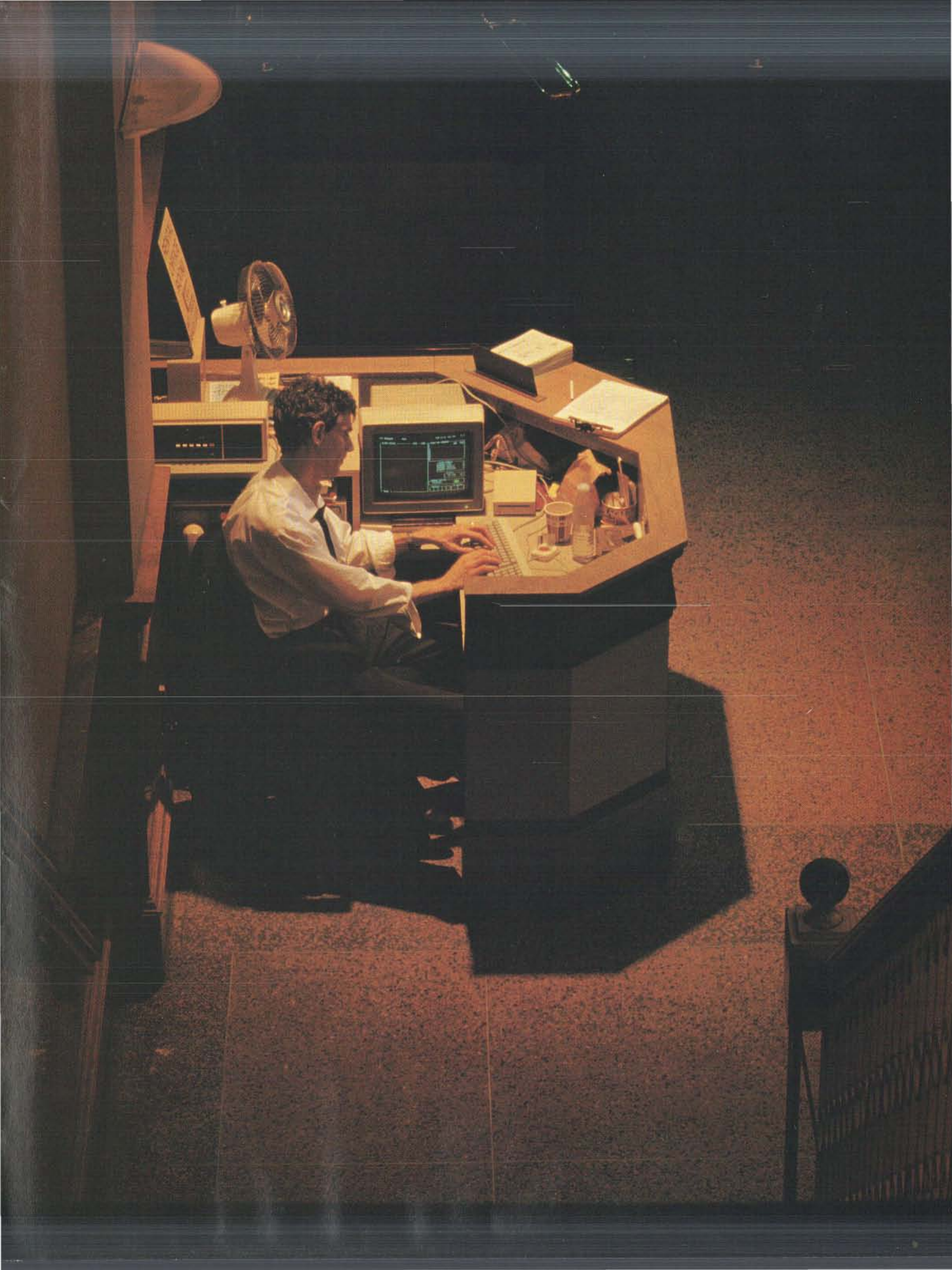
We and various colleagues are working to understand how computer networks can affect the nature of work and relationships between managers and employees. What we are learning may help people to exploit better the opportunities that networks offer and to avoid or mitigate the potential pitfalls of networked organizations.

Our research relies on two approaches. Some questions can be studied through laboratory experiments. For instance, how do small groups respond emotionally to different forms of communication? Other questions, particularly those concerning organizational change, require field studies in actual organizations that have been routinely using computer networks. Data describing how hundreds of thousands of people currently use network communications can help predict how other people will work in the future as computer-based communications become more prevalent. Drawing on field studies and experiments, researchers gradually construct a body of evidence on how work and organizations are changing as network technology becomes more widely used. The process may sound straightforward, but in reality it is often full of exciting twists. People use technology in surprising ways, and effects often show up that contradict both theoretical predictions and managerial expectations.

One major surprise emerged as soon as the first large-scale computer network, known as the ARPANET, was begun in the late 1960s. The ARPANET was developed for the Advanced Research Projects Agency (ARPA), a part of the U.S. Department of Defense. ARPANET was intended to link computer scientists at universities and other research institutions to distant computers, thereby permitting efficient access to machines unavailable at the home institutions. A facility called electronic mail, which enabled researchers

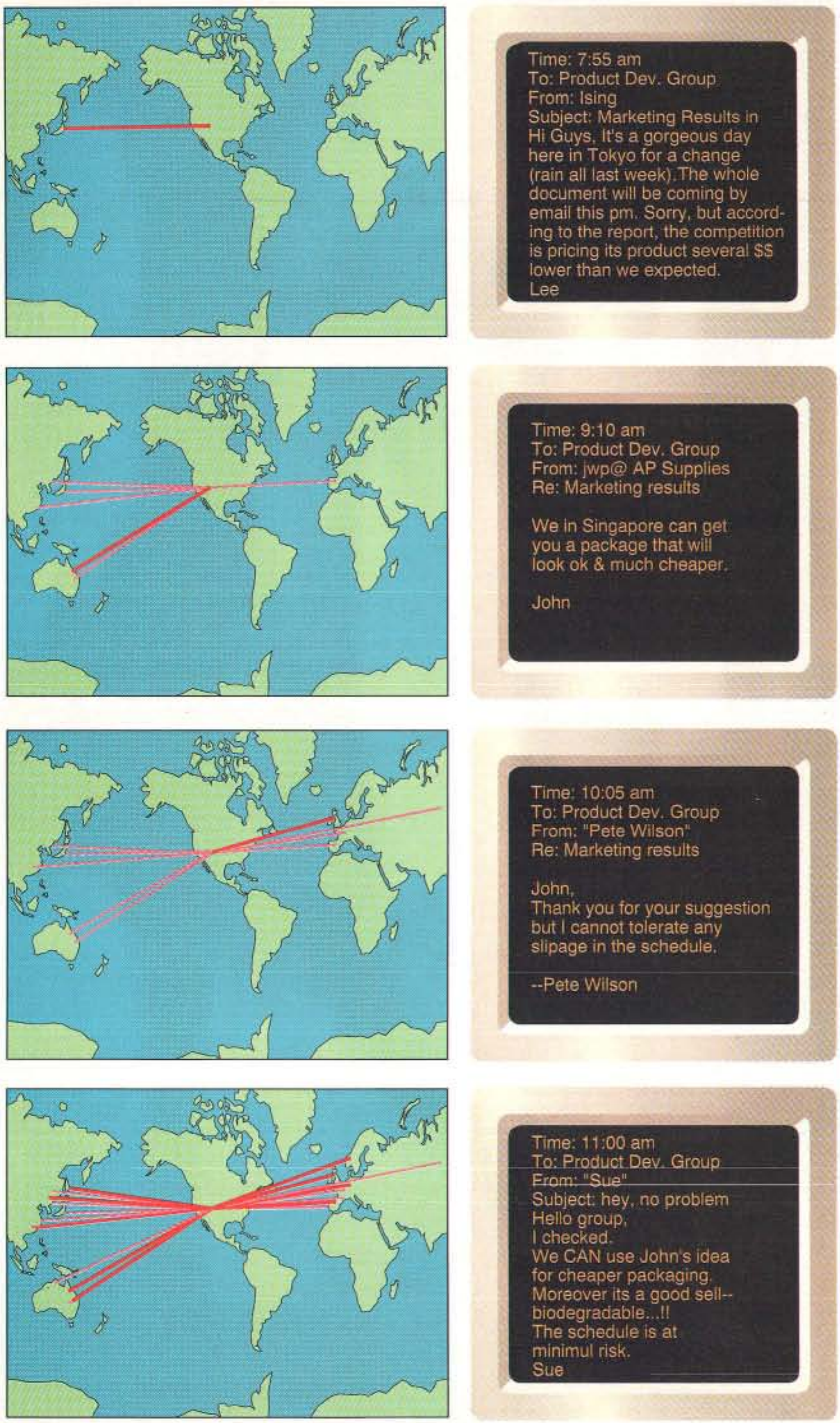
LEE SPROULL and SARA KIESLER have spent more than a decade studying established electronic mail communities to learn about how they change patterns of communication within organizations. Sproull received a Ph.D. in social science from Stanford University in 1977. Until this year she was a professor of social sciences and sociology at Carnegie Mellon University. She is now a professor of management at Boston University's School of Management. Kiesler completed a Ph.D. in social psychology at Ohio State University in 1965. In 1979 she joined the faculty of Carnegie Mellon University, where she is a professor of social sciences and social psychology, as well as a member of the university's robotics institute.

ISOLATED EMPLOYEES, such as a night watchman, benefit in particular from computer network links. Networks can create a web of social connections that stretch across time and that exist independently of an employee's physical location or hierarchical position. Because of the lack of social cues, people communicating electronically tend to talk more freely than they would in person. Networks potentially permit broader access to information and more democratic structures than are now found in most organizations. Exploiting that potential will force managers to grapple with issues of responsibility and control.



How People Work via Electronic Mail

Global communication is possible using computer networks and electronic mail, as illustrated by the behavior of "Sue Jones," a composite based on a number of workers studied by the authors. On a typical day, Jones sends and receives from 25 to 100 pieces of electronic mail that cover both business and social topics. The maps record the links made during the course of the day, highlighting those associated with one of her working groups; the computer screens show the messages she sends to and receives from that working group. In this case, a potential crisis in the pricing of a new product is quickly resolved via electronic communication. Networks permit close, ongoing cooperation among coworkers who are physically located in very different corners of the globe.



to communicate with one another, was considered a minor additional feature of the network.

Yet electronic mail rapidly became one of the most popular features of the ARPANET. Computer scientists around the country used ARPANET to exchange ideas spontaneously and casually. Graduate students discussed problems and shared skills with professors and other students without regard to their physical location. Heads of research projects used electronic mail to coordinate activities with project members and to stay in touch with other research teams and funding agencies. A network community quickly formed, filled with friends and collaborators who rarely, if ever, met in person. Although some administrators objected to electronic mail because they did not consider it a legitimate use of computer time, demand grew sharply for more and better network connections.

Since then, many organizations have adopted internal networks that link anywhere from a few to a few thousand employees. Some of these organizational networks have also been connected to the Internet, the successor to ARPANET. Electronic mail has continued to be one of the most popular features of these computer networks.

Anyone who has a computer account on a networked system can use electronic mail software to communicate with other users on the network. Electronic mail transmits messages to a recipient's electronic "mailbox." The sender can send a message simultaneously to several mailboxes by sending the message to a group name or to a distribution list. Electronic bulletin boards and electronic conferences are common variants of group electronic mail; they too have names to identify their topic or audience. Bulletin boards post messages in chronological order as they are received. Computer conferences arrange messages by topic and display grouped messages together.

The computer communications technology in most networked organizations today is fairly similar, but there exist large differences in people's actual communication behavior that stem from policy choices made by management. In some networked organizations, electronic mail access is easy and open. Most employees have networked terminals or computers on their desks, and anyone can send mail to anyone else. Electronic mail costs are considered part of general overhead expenses and are not charged to employees or to their departments. In the open-network organizations we have studied, people typically send and receive between 25

and 100 messages a day and belong to between 10 and 50 electronic groups. These figures hold across job categories, hierarchical position, age and even amount of computer experience.

In other networked organizations, managers have chosen to limit access or charge costs directly to users, leading to much lower usage rates. Paul Schreiber, a *Newsday* columnist, describes how his own organization changed from an open-access network to a limited-access one. Management apparently believed that reporters were spending too much time sending electronic mail; management therefore had the newspaper's electronic mail software modified so that reporters could still receive mail but could no longer send it. Editors, on the other hand, could still send electronic mail to everyone. Clearly, technology by itself does not impel change. Management choices and policies are equally influential.

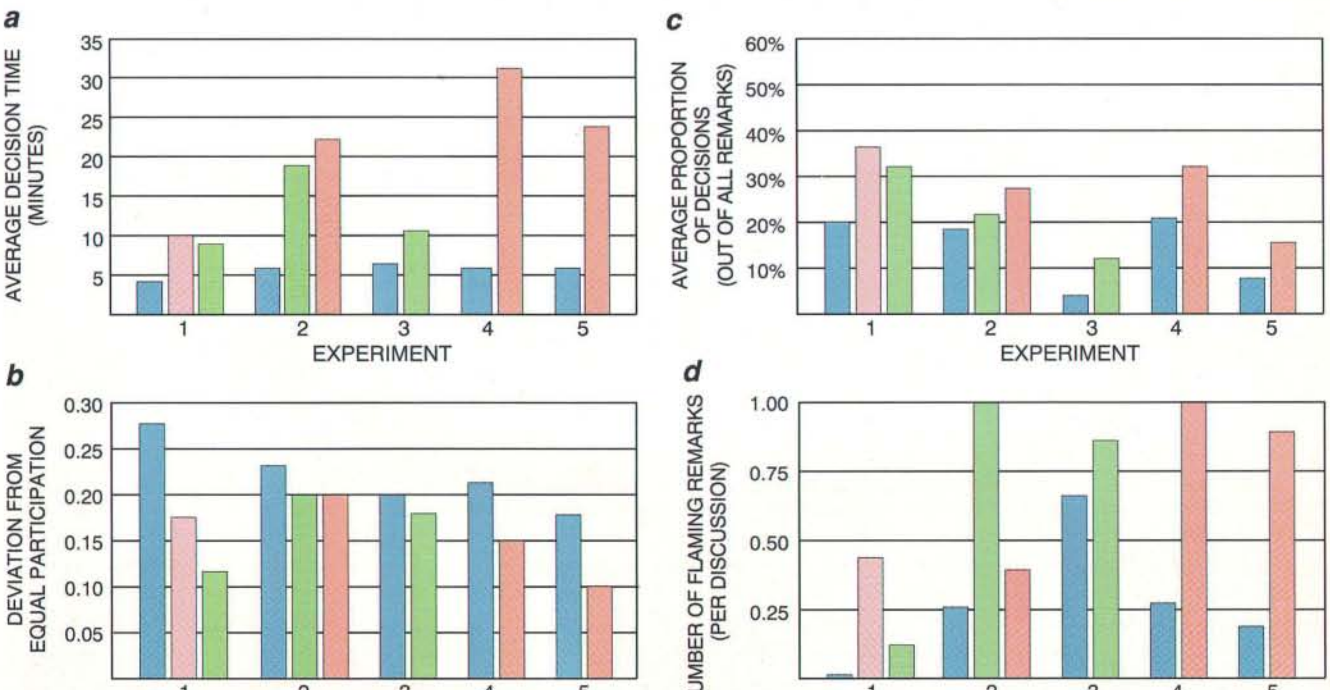
But even in organizations that have open access, anticipating the effect of networks on communication has proved no easy task. Some of the first researchers to study computer network communications thought the technology would improve group decision making over face-to-face discussion because computer messages were plain text. They reasoned that electronic discussions would be more purely intellectual, and so decision making would be less affected by people's social skills and personal idiosyncracies.

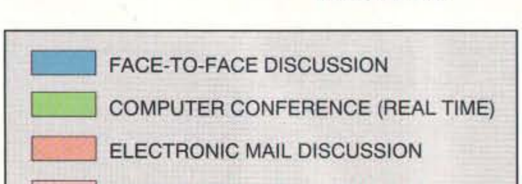
Research has revealed a more complicated picture. In an electronic exchange, the social and contextual cues that usually regulate and influence group dynamics are missing or attenuated. Electronic messages lack information regarding job titles, social importance, hierarchical position, race, age and appearance. The context also is poorly defined because formal and casual exchanges look essentially the same. People may have outside information about senders, receivers and situations, but few cues exist in the computer interaction itself to remind people of that knowledge.

In a series of experiments at Carnegie Mellon University, we compared how small groups make decisions using computer conferences, electronic mail and face-to-face discussion [*see illustration below*]. Using a network induced the participants to talk more frankly and more equally. Instead of one or two people doing most of the talking, as happens in many face-to-face groups, everyone had a more equal say. Furthermore, networked groups generated more proposals for action than did traditional ones.

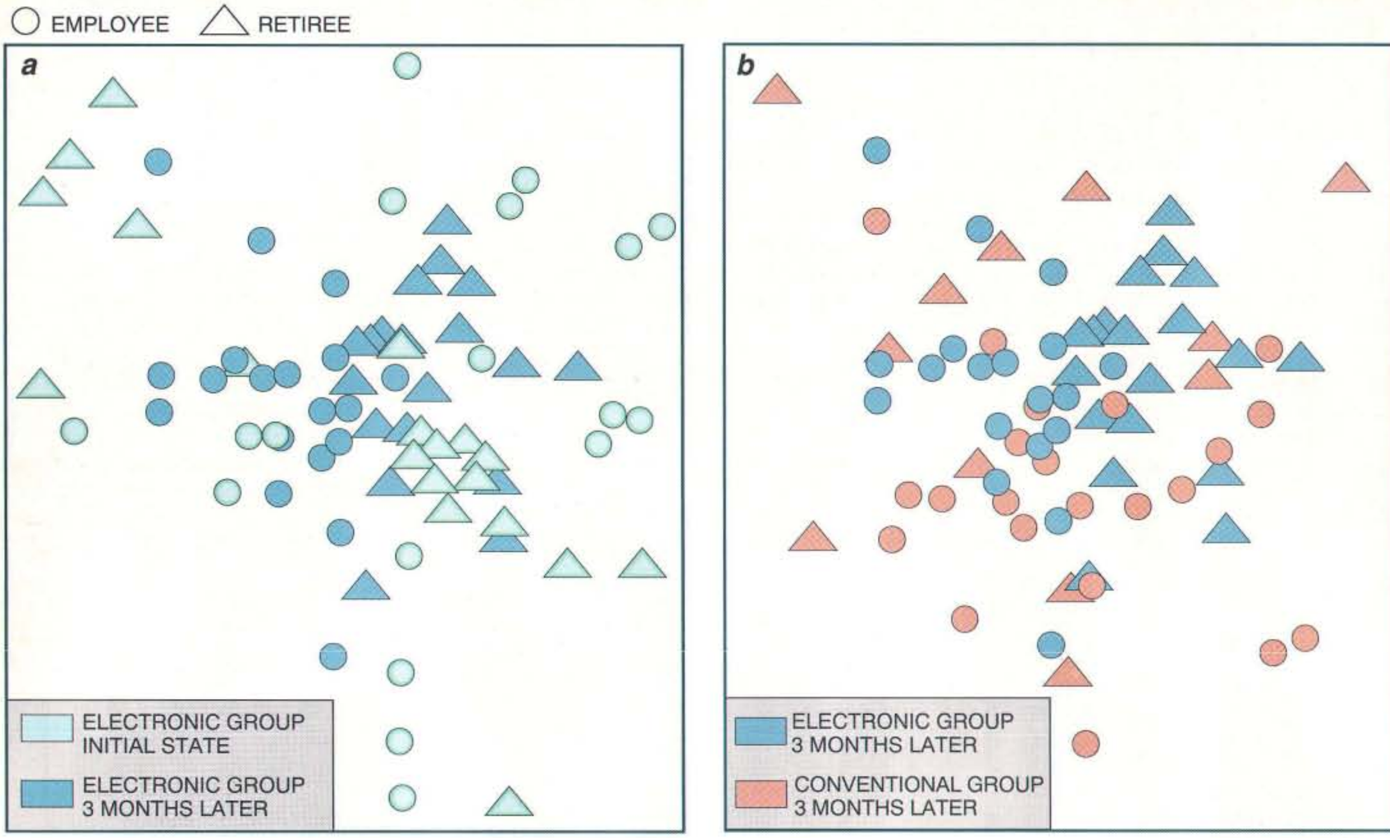
Open, free-ranging discourse has a dark side. The increased democracy associated with electronic interactions in our experiments interfered with decision making. We observed that three-person groups took approximately four times as long to reach a decision electronically as they did face-to-face. In one case, a group never succeeded in reaching consensus, and we were ultimately forced to terminate the experiment. Making it impossible for people to interrupt one another slowed decision making and increased conflict as a few members tried to dominate control of the network. We also found that people tended to express extreme opinions and vented anger more openly in an electronic face-off than when they sat together and talked. Computer scientists using the ARPANET have called this phenomenon "flaming."

We discovered that electronic communication can influence the effects of people's status. Social or job position normally is a powerful regulator of group interaction. Group members typ-





LABORATORY STUDIES reveal some ways in which networks affect how people work together. Ninety-four groups of subjects in five experiments were told to reach consensus decisions on several questions. Each group made some decisions electronically (through one or two network modes) and others face-to-face. When networked, all groups took longer to make a decision (*a*). On the other hand, they enjoyed more equal participation (*b*) and proposed more ideas (*c*). The electronic modes of discussion seemed to encourage "flaming," impassioned self-expression (*d*).



ically defer to those who have higher status and tend to follow their direction. Members' speech and demeanor become more formal in the presence of people who have high status. Higher-status people, in turn, talk more and influence group discussion more than do lower-status people.

Given that electronic conversations attenuate contextual cues, we expected that the effect of status differences within a group should also be reduced. In an experiment conducted with Vitaly Dubrovsky of Clarkson University and Beheruz Sethna of Lamar University, we asked groups containing high- and low-status members to make decisions both by electronic mail and face-to-face. The results confirmed that the proportion of talk and influence of higher-status people decreased when group members communicated by electronic mail.

Is this a good state of affairs? When higher-status members have less expertise, more democracy could improve decision making. If higher-status members truly are better qualified to make decisions, however, the results of consensus decisions may be less good.

Shoshanah Zuboff of Harvard Business School documented reduced effects of status on a computer conference system in one firm. People who regarded themselves as physically unattractive reported feeling more lively and confident when they expressed themselves over the network. Others who had soft voices or small stature reported that they no longer had to struggle to be taken seriously in a meeting.

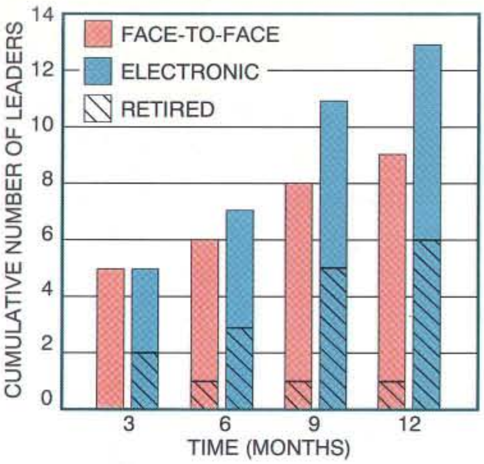
Researchers have advanced alternative explanations for the openness and democracy of electronic talk. One hypothesis is that people who like to use computers are childish or unruly, but this hypothesis does not explain experimental results showing that the same people talk more openly on a computer than when they are face-to-face. Another hypothesis holds that text messages require strong language to get a point across; this hypothesis explains flaming but not the reduction of social and status differences. The most promising explanation of the behavior of networked individuals is that when cues about social context are absent or weak, people ignore their social situation and cease to worry about how others evaluate them. Hence, they devote less time and effort to posturing and social niceties, and they may be more honest.

Researchers have demonstrated decreased social posturing in studies that ask people to describe their own behavior. In one of our experiments, people were asked to complete a self-evaluation questionnaire either by pencil and paper or via electronic mail. Those randomly assigned to reply electronically reported significantly more undesirable social behaviors, such as illegal drug use or petty crimes. John Greist and his colleagues at the University of Wisconsin found similar decreases in posturing when taking medical histories from clinical patients. People who responded to a computerized patient history interview revealed more socially and physically undesirable behavior than did those who answered the same questions asked by a physician.

These studies show that people are willing to reveal more about undesirable symptoms and behavior to a computer, but are these reports more truthful? An investigation of alcohol consumption conducted by Jennifer J. Waterton and John C. Duffy of the University of Edinburgh suggests an affirmative answer. In traditional surveys, people report drinking only about one half as much alcohol as alcohol sales figures would suggest. Waterton and Duffy compared computer interviews with personal interviews in a survey of alcohol consumption. People who were randomly assigned to answer the computer survey reported higher alcohol consumption than those who talked to the human interviewer. The computer-derived reports of consumption extrapolated more accurately to actual alcohol sales than did the face-to-face reports.

These and other controlled studies of electronic talk suggest that such communication is relatively impersonal, yet paradoxically, it can make people feel more comfortable about talk-

c



DYNAMIC GROUP STRUCTURES emerge when people converse electronically. These charts depict the behavior of two study groups, each containing a mix of employees and retired workers. One group worked in person, the other over a network. Members having the most information and social contacts appear near the center of the charts. Over time, the electronic group becomes more socially cohesive (*a*). Chart *b* compares the electronic group with the conventional group three months into the project and shows that retirees in particular become better integrated in the electronic group. Networks also encouraged more people to take on leadership roles (*c*).

ing. People are less shy and more playful in electronic discussions; they also express more opinions and ideas and vent more emotion.

Because of these behavioral effects, organizations are discovering applications for electronic group activities that nobody had anticipated. Computers can be valuable for counseling and conducting surveys about sensitive topics, situations in which many people are anxious and cover their true feelings and opinions. Networks are now being used for applications ranging from electronic Alcoholics Anonymous support groups to electronic quality circles.

Just as the dynamics of electronic communications differ from those conducted orally or by letters, so electronic groups are not just traditional groups whose members use computers. People in a networked organization are likely to belong to a number of electronic groups that span time zones and job categories. Some of these groups serve as extensions of existing work groups, providing a convenient way for members to communicate between face-to-face meetings. Other electronic groups gather together people who do not know one another personally and who may in fact have never had the opportunity to meet in person.

For example, Hewlett-Packard employs human-factors engineers who work in widely scattered locations around the world. These engineers may meet one another in person only once a year. An electronic conference creates ongoing meetings in which they can frequently and routinely discuss professional and company issues.

In some ways, electronic groups resemble nonelectronic social groups. They support sustained interactions, develop their own norms of behavior and generate peer pressure. Electronic groups often have more than 100 members, however, and involve relationships among people who do not know one another personally.

Employees whose organization is connected to the Internet or to a commercial network can belong to electronic groups whose members come from many different organizations. For example, Brian K. Reid of Digital Equipment Corporation reports that some 37,000 organizations are connected to USENET, a loosely organized network that exchanges more than 1,500 electronic discussion groups, called newsgroups. Reid estimates that 1.4 million people worldwide read at least one newsgroup.

Networked communication is only beginning to affect the structure of the workplace. The form of most current organizations has been dictated by the constraints of the nonelectronic world. Interdependent jobs must be situated in physical proximity. Formal command structures specify who reports to whom, who assigns tasks to whom and who has access to what information. These constraints reinforce the centralization of authority and shape the degree of information sharing, the number of organizational levels, the amount of interconnectivity and the structure of social relationships.

Organizations that incorporate computer networks could become more flexible and less hierarchical in structure. A field experiment conducted by Tora K. Bikson of Rand Corporation and John D. Eveland of Claremont Colleges supports the point. They formed two task forces in a large utility firm, each assigned to analyze employee retirement issues. Both groups contained 40 members, half of whom had recently retired from the company and half of whom were still employed but eligible for retirement. The only difference between the two groups was that one worked on networked computer facilities, whereas the other did not.

Both task forces created subcommittees, but the networked group created more of them and assigned people to more than one subcommittee. The networked group also organized its subcommittees in a complex, overlapping matrix structure. It added new subcommittees during the course of its work, and it decided to continue meeting even after its official one-year life span had ended. The networked task force also permitted greater input from the retirees, who were no longer located at the company. Although not every electronic group will be so flexible, eliminating the constraints of face-to-face meetings evidently facilitates trying out different forms of group organization.

Another effect of networking may be changed patterns of information sharing in organizations. Conventional organizations have formal systems of record keeping and of responsibilities for distributing information. Much of the information within an organization consists of personal experience that never appears in the formally authorized distribution system: the war stories told by service representatives (which do not appear in service manuals), the folklore about how the experimental apparatus really works (which does not appear in the journal articles) or the gossip about how workers should behave (which is not described in any personnel policy).

In the past, the spread of such personal information has been strongly determined by physical proximity and social acquaintance. As a result, distant or poorly connected employees have lacked access to local expertise; this untapped knowledge could represent an important informational resource in large organizations. Electronic groups provide a forum for sharing such expertise independent of spatial and social constraints.

One significant kind of information flow begins with the "Does anybody know...?" message that appears frequently on computer networks. A sender might broadcast an electronic request for information to an entire organization, to a particular distribution list or to a bulletin board. Anyone who sees the message can reply. We studied information inquiries on the network at Tandem Computers, Inc., in Cupertino, Calif., a computer company that employs 10,500 workers around the world. In a study we conducted with David Constant, we found an average of about six does-anybody-know messages broadcast every day to one company-wide distribution list.

Information requests typically come from field engineers or sales representatives who are soliciting personal ex-

perience or technical knowledge that they cannot find in formal documents or in their own workplace. At Tandem, about eight employees send electronic mail replies to the average question. Fewer than 15 percent of the people who answer a question are personally acquainted with the questioner or are even located in the same city.

Question askers can electronically redistribute the answers they receive by putting them in a public computer file on the network. About half of the Tandem questioners make their reply files publicly available over the company network to other employees. Tandem takes this sharing process one step further by maintaining an electronic archive of question-and-reply files that is also accessible over the company network. The firm has thereby created a repository of information and working expertise that is endlessly accessible through space and time (for example, the expertise remains available when an employee is out of the office or he or she leaves the organization). A study by Thomas Finholt in our research program found that this archive is accessed more than 1,000 times a month by employees, especially those located in field offices away from the geographic center of the company.

The discretionary information sharing we discovered at Tandem and at other networked organizations seems to run contrary to nonelectronic behavior in organizations. The askers openly admit their ignorance to perhaps hundreds or even thousands of people. The repliers respond to requests for help from people they do not know with no expectation of any direct benefit to themselves.

One might wonder why people respond so readily to information requests made by strangers. Part of the explanation is that networks make the cost of responding extremely low in time and effort expended. Also, open-access networks favor the free flow of information. Respondents seem to believe that sharing information enhances the overall electronic community and leads to a richer information environment. The result is a kind of electronic altruism quite different from the fears that networks would weaken the social fabric of organizations.

The changes in communication made possible by networks may substantially alter the relationship between an employee and his or her organization, the structure of organizations and the nature of management. Senior managers and key professionals usually have strong social and informational connections within their organizations and within their broader professional communities. Conversely, employees who reside on the organizational periphery by virtue of geographic location, job requirements or personal attributes have relatively few opportunities to make contact with other employees and colleagues.

Reducing the impediments to communication across both physical and social distance is likely to affect peripheral employees more than central ones. We, along with Charles Huff of St. Olaf College, studied this possibility for city employees in Fort Collins, Colo. Employees who used electronic mail extensively reported more commitment to their jobs and to their co-workers than did those who rarely used the network. This correlation was particularly strong for shift workers, who, because of the nature of their work, had fewer opportunities to see their colleagues than did regular day workers. As one policewoman told us,

ELECTRONIC LINKS have the greatest effect on workers located at outlying sites. Workers in field offices of Tandem Computers, Inc., whose headquarters are in Cupertino, Calif., have access to data files via a network. Circles indicate how many times each office tapped into one file (consisting of employee-initiated questions and answers about company products and services) over a one-year period; the greater the usage, the larger the circle. Workers in distant or isolated offices, where local expertise is relatively limited, made the most use of the information provided through the network.

"Working the night shift, it used to be that I would hear about promotions after they happened, though I had a right to be included in the discussion. Now I have a say in the decision making."

Organizations are traditionally built around two key concepts: hierarchical decomposition of goals and tasks and the stability of employee relationships over time. In the fully networked organization that may become increasingly common in the future, task structures may be much more flexible and dynamic. Hierarchy will not vanish, but it will be augmented by distributed lattices of interconnections.

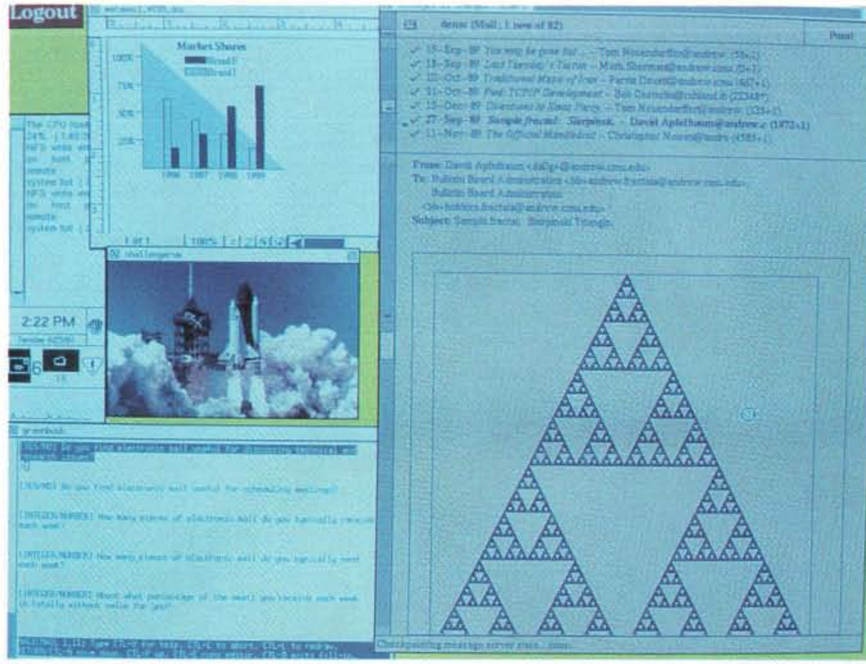
In today's organizations, executives generally know whom they manage and manage whom they know. In the future, however, managers of some electronic project groups will face the challenge of working with people they have never met. Allocating resources to projects and assigning credit and blame for performance will become more complex. People will often belong to many different groups and will be able to reach out across the network to acquire resources without management intervention or perhaps even without management knowledge.

A recent case in mathematics research hints at the nature of what may lie ahead. Mathematicians at Bell Communications Research (Bellcore) and at Digital Equipment sought to factor a large, theoretically interesting number known as the 9th Fermat number. They broadcast a message on the Internet to recruit researchers from universities, government laboratories and corporations to assist them in their project. The several hundred researchers who volunteered to help received—via electronic mail—software and a piece of the problem to solve; they also returned their solutions through electronic mail.

After results from all the volunteers were combined, the message announcing the final results of the project contained a charming admission:

> We'd like to thank everyone who contributed computing cycles to this project, but I can't: we only have records of the person at each site who installed and managed the code. If you helped us, we'd be delighted to hear from you; please send us your name as you would like it to appear in the final version of the paper. (Broadcast message from Mark S. Manasse, June 15, 1990.)

Networking in most organizations today is limited to data communications, often for economic or financial applications such as electronic data interchange, electronic funds transfer or remote transaction processing. Most organizations have not yet begun to confront the opportunities and challenges afforded by connecting their employees through networks.



ADVANCED ELECTRONIC MAIL, such as this experimental setup at Bellcore, will make it possible to transmit graphics, animation, self-contained computer programs and audio recordings. Such features will broaden the applications for networked communications. They may also restore some of the social cues now absent from electronic mail and thereby modify the behavior of its users.

Among those that have, managers have responded in a variety of ways to changes that affect their authority and control. Some managers have installed networks for efficiency reasons but ignored their potential for more profound changes. Some have restricted who can send mail or have shut down electronic discussion groups. Others have encouraged using the network for broadening participation and involving more people in the decision-making process. The last actions push responsibility down and through the organization and also produce their own managerial issues.

A democratic organization requires competent, committed, responsible employees. It requires new ways of allocating credit. It increases unpredictability, both for creative ideas and for inappropriate behavior. Managers will have to come up with new kinds of worker incentives and organizational structures to handle these changes.

The technology of networks is changing rapidly. Electronic mail that includes graphics, pictures, sound and video will eventually become widely available. These advances will make it possible to reintroduce some of the social context cues absent in current electronic communications. Even so, electronic interactions will never duplicate those conducted face-to-face.

As more people have ready access to network communications, the number and size of electronic groups will expand dramatically. It is up to management to make and shape connections. The organization of the future will depend significantly not just on how the technology of networking evolves but also on how managers seize the opportunity it presents for transforming the structure of work.

FURTHER READING

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IN INCREASINGLY COMPETITIVE MARKETS, TELEKOM COOPERATES WITH INTERNATIONAL PARTNERS

The Commission of the European Community has predicted that the telecom share of EC-wide GNP will double from just under three percent in 1984 to about seven percent in 1999. Overall telecom revenues, worldwide, should rise from US $392 billion (1990) to US $865 billion by this decade's end. TELEKOM is responding with joint ventures with its European neighbors: a new high-capacity optical fiber link across the Atlantic (in service 1992, the first direct link to Germany), a new electronic data interchange service (EDI) in Europe and a system to help deliver "electronic brochures" and catalogues to European travel agents.

Germany is strategically sited for multinationals setting up in Europe, its attractiveness enhanced by reunification. Options such as one-stop shopping, single-end billing and network management are concepts being brought into reality, in part with partners like British Telecom. Within the past year, TELEKOM has upgraded its international presence by opening offices in Tokyo, New York, London, Paris and Brussels. Components and equipment are increasingly being procured abroad: two examples are digital mobile radio and intelligent networks.

Furthermore, **TELEKOM** is actively pursuing market opportunities in the Soviet Union, Czechoslovakia and Poland. The firm's guiding principle is to open these markets for European businesses. An example: Trans Europe Line (TEL) — this fiber link runs from Frankfurt to Warsaw, Prague and Budapest and is scheduled to go into service by the end of 1993.

TELEKOM IS COMMITTED TO A LEADING ROLE IN TELECOMMUNICATIONS RESEARCH

TELEKOM is grounded in technological innovation, concentrating on specialization and differentiation of products and services. Two examples: introduction this year of the cellular D-network and of "Modacom," a mobile data transmission service.

An important role has been undertaken in Eurescom, at Heidelberg (the first European telecommunications body based in Germany), a research organization founded by 20 network operators from 16 countries. Established to further a "harmonized" network across Europe, Eurescom aims to develop a suitable expansion strategy, to further research by linking projects underway in existing facilities maintained by members and to generate pilot projects in order to demonstrate the viability of research results. As networks expand using compatible standards, customers are better served and operating costs lowered.

TELEKOM's own Research Institute in Darmstadt and Berlin is working in semiconductor technologies, the use of digital switches and the use of optical fiber cables. One key thrust is to lower the cost of optical fiber at the subscriber level. By 1990, TELEKOM had installed 1.02 million kilometers of optical fiber in trunk and local networks. The next step for use of fiber optics is for TELEKOM to perfect a technology compatible with existing networks, one that is open to feeding-in and feeding-out of the laser signal. This new phase must have a high failsafe protection against faults and cable interruptions and allow upgrading to broadband service. Currently, TELEKOM is testing specific optical fiber network architectures from various suppliers in a series of pilot projects (called OPAL), launched in 1990, designed to evaluate broadband distribution service, analogue telephone and switched telecommunications service. Cost-saving mass production can begin as soon as standardization of the interfaces with the switching equipment, splitters to be used and wavelength allocations are established.

TELEKOM'S FUTURE LOOKS BRIGHT

TELEKOM confronts a difficult phase in its history. And yet, the firm is secure that its applications of high-tech solutions wherever feasible, its cutting-edge research, and commitment to international collaborations will allow it successfully to meet increased competition at home and abroad. All this while allowing creation of a sophisticated communications network in eastern Germany. TELEKOM's senior management team's successful track record bodes very well for the company's future as a major corporate player in the expanding, and evermore challenging, global telecommunications market. ◆

Computers, Networks and the Corporation

Computer networks are forging new kinds of markets and new ways to manage organizations. The result will be a major change in corporate structure and management style

by Thomas W. Malone and John F. Rockart

About 150 years ago the economy in the U.S. and Europe began to undergo a period of change more profound than any experienced since the end of the Middle Ages. We call that change the Industrial Revolution. The industrial economies are now in the early stages of another transformation that may ultimately be at least as significant.

There is a critical difference this time, however. Changes in the economies of production and transportation drove the revolution of the last century. The revolution under way today will be driven not by changes in production but by changes in coordination. Whenever people work together, they must somehow communicate, make decisions, allocate resources and get products and services to the right place at the right time. Managers, clerks, salespeople, buyers, brokers, accountants—in fact, almost everyone who works—must perform coordination activities.

It is in these heavily information-based activities that information technologies have some of their most important uses, and it is here that they will have their most profound effects. By dramatically reducing the costs of coordination and increasing its speed and quality, these new technologies will enable people to coordinate more effectively, to do much more coordination and to form new, coordination-intensive business structures.

The core of the new technologies is the networked computer. The very name "computer" suggests how one usually thinks of the device—as a machine for computing, that is, for taking in information, performing calculations and then presenting the results. But this image of computing does not capture the essence of how computers are used now and how they will be used even more in the future. Many of the most important uses of computers today are for coordination tasks, such as keeping track of orders, inventory and accounts. Furthermore, as computers become increasingly connected to one another, people will find many more ways to coordinate their work. In short, computers and computer networks may well be remembered not as technology used primarily to compute but as coordination technology.

THOMAS W. MALONE and JOHN F. ROCKART, both at the Massachusetts Institute of Technology, study the effects of computer technology on business. Malone, who directs the Center for Coordination Science at M.I.T., received his Ph.D. from Stanford University and holds degrees in applied mathematics, engineering and psychology. He was previously a research scientist at the Xerox Palo Alto Research Center. Rockart received his M.B.A. from Harvard University and his Ph.D. from M.I.T., where he directs the Center for Information Systems Research. He serves on the board of directors of five organizations and lectures at several major companies.

To understand what is likely to happen as information technology improves and its costs decline, consider an analogy with a different technology: transportation. A first-order effect of transportation technology was simply the substitution of new transportation technologies for the old. People began to ride in trains and automobiles rather than on horses and in horse-drawn carriages.

As transportation technology continued to improve, people did not use it just to substitute for the transportation they had been using all along. Instead a second-order effect emerged: people began to travel more. They commuted farther to work each day. They were more likely to attend distant business meetings and to visit faraway friends and relatives.

Then, as people used more and more transportation, a third-order effect eventually occurred: the emergence of new "transportation-intensive" social and economic structures. These structures, such as suburbs and shopping malls, would not have been possible without the wide availability of cheap and convenient transportation.

Improved coordination technology has analogous effects. A first-order effect of reducing coordination costs is the substitution of information technology for human coordination. For example, data-processing systems helped to eliminate thousands of clerks from the back offices of insurance companies and banks. Similarly, computer-based systems have replaced scores of factory "expediters." Today computers track the priority of each job in the factory and indicate the most critical ones at each workstation. More generally, the long-standing prediction that computers will lead to the demise of middle management finally seems to be coming true. In the 1980s many companies flattened their managerial hierarchies by eliminating layers of middle managers.

A second-order effect of reducing coordination costs is an increase in the overall amount of coordination used. For instance, contemporary airline res-

TRADING FLOOR of the Paris Stock Exchange bustles with activity (*top*), much as do those of other exchanges. In contrast, the floor of the London International Stock Exchange, where trading is electronic, is quite leisured in pace (*bottom*). The distinction reflects how networks and coordination technology have begun to restructure the way businesses conduct transactions.


Groupe D
Groupe E

ervation systems enable travel agents to consider more flight possibilities for a given customer more easily. These systems have led to an explosion of special fares and price adjustments. American Airlines and United Air Lines, which provide the largest systems, have benefited significantly from the fees they charge for this service. For instance, in 1988 American made about \$134 million from its reservation system—almost 15 percent of its total income. In addition, access to up-to-the-minute information about ticket sales on all airlines enables American and United to adjust their fare schedules to maximize profits.

Otis Elevator Company also increased the amount of its coordination—primarily to improve maintenance service for its customers. With its Otisline system, highly trained multilingual operators receive trouble calls through a national toll-free number. The operators record the problems in a computer data base and then electronically dispatch local repair people.

This real-time availability of data has vastly improved the management of repair activities. For instance, if a particular type of part has failed during the past week on eight of 100 elevators, Otis can preemptively replace that part on the other 92 elevators. Although this kind of nationwide correlation of data was possible before, the degree of communication and coordination required was impractical. These capabilities have played a major role in reducing maintenance calls by nearly 20 percent.

In some instances, the second-order effect of an increase in demand may overwhelm the first-order effect of substitution. For example, in one case we studied, a computer conferencing system helped to remove a layer of middle managers. Several years later, however, almost the same number of new positions (for different people at the same grade level) had been created. According to people in the company, the new specialists took on projects not considered before. Evidently, managerial resources no longer needed for simple communication could now be focused on more complex coordination tasks.

A third-order effect of reducing coordination costs is a shift toward the use of more coordination-intensive structures. A prime example is Frito-Lay, Inc., studied by Lynda M. Applegate of Harvard Business School and others. At Frito-Lay, some 10,000 route salespeople record all sales of each of 200 grocery products on hand-held computers as they deliver goods to customers on their route. Each night, the stored information is transmitted to a central computer. In turn, the central computer sends information on changes in pricing and product promotions to the hand-held computers for use the next day. Each week, the main computer summarizes the centrally stored information and combines it with external data about the sales of competitive brands. Some 40 senior executives and others can then gain access to this information through an executive information system (EIS).

The availability of these data has enabled Frito-Lay to push key decisions down from corporate headquarters to four area heads and several dozen district managers. The managers can use the data not only to compare actual sales to sales targets but also to recommend changes in sales strategy to top management. This entire coordination-intensive structure has become possible only in the past few years because of the improved capability and reduced costs of hand-held computers, EIS software, computer cycles and telecommunications equipment.

Coordination-intensive structures do not just link different people in the

RESERVATION CENTER of Rosenbluth Travel in Philadelphia transmits travel information to a "back room," which coordinates activities of other agencies from around the world. Information about demand becomes available immediately, enabling the connected firms to respond to the market more effectively and profitably than can isolated agencies.

ROUTE SALESMAN of Frito-Lay, Inc., enters inventory data into a hand-held computer. The information will be combined with similar data from 10,000 other salespeople and made accessible to management the next morning. The rapid availability of data has enabled Frito-Lay to decentralize pricing and inventory decisions. Instead of corporate headquarters, four area heads and the district managers set prices, and the salespeople determine the product mix.

same companies. Many of the most interesting new structures involve links among different companies. For example, the U.S. textile industry has begun implementing a series of electronic connections among companies as part of the Quick Response program. As described by Janice H. Hammond of Harvard Business School and others, these electronic connections link companies all along the production chain, from suppliers of fibers (such as wool and cotton) to the mills that weave these fibers into fabric, to the factories that sew garments and, ultimately, to the stores that sell the garments to consumers.

When such networks are fully implemented, they will help companies respond quickly to demand. For instance, when a sweater is sold in New York City, a scanner reading the bar-coded label may automatically trigger ordering, shipping and production activities all the way back to the wool warehouse in South Carolina. This new, multiorganizational structure will reduce inventory costs throughout the value chain. The textile-apparel retail industry spends about $25 billion in inventory costs every year; the Quick Response approach may save half that amount.

Wal-Mart has already established parts of a similar system that links the retailer to Procter & Gamble Company and several of its other major suppliers. In doing so, Wal-Mart has eliminated significant parts of its own purchasing groups and contracted with its suppliers to replace products as they are sold. In one such experiment, both unit sales and inventory turnover increased by about 30 percent.

Sometimes technology helps to create interorganizational networks—not just among buyers and suppliers but also among potential competitors. For example, Eric K. Clemons of the University of Pennsylvania has studied the Rosenbluth International Alliance, a consortium of travel agencies around the world that share customer records, services and software. The alliance also provides clients with toll-free English-language help lines in every major country. This consortium of independent agencies, led by Rosenbluth Travel in Philadelphia, can therefore manage all travel arrangements for international trips and for meetings of people from many parts of the globe.

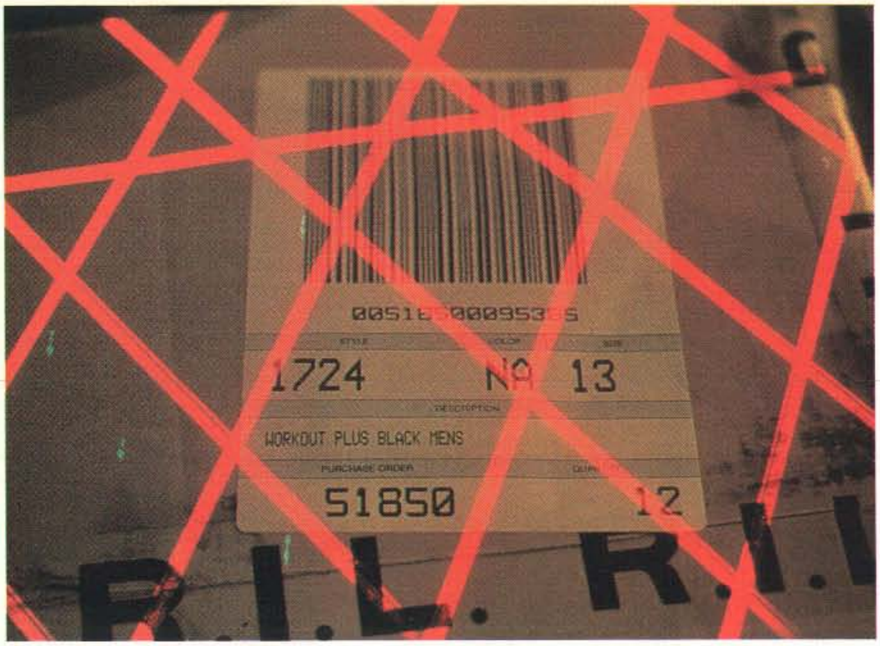
The textile firms near Prato, Italy, illustrate a related kind of interoganizational alliance. As described by Michael J. Piore and Charles F. Sabel of the Massachusetts Institute of Technology, the operation of a few large textile mills was broken into many small firms, coordinated in part by electronic connections among them. This network can flexibly adjust to changes in demand, sometimes shifting orders from an overloaded mill to one with spare capacity. The structure also takes advantage of the entrepreneurial motivation of the owners: in small mills, the owners' rewards are more closely linked to their own efforts than is the case in large ones.

As these examples show, information technology is already facilitating the emergence of new, coordination-intensive structures. What do these changes mean for the organizations of the near future?

A surprising result of our research is a prediction that information technology should lead to an overall shift from internal decisions within firms toward the use of markets to coordinate economic activity. To see why, consider that all organizations must choose between making the goods or services they need and buying them from outside suppliers. For instance, General Motors Corporation must decide whether to make tires internally or purchase them from a tire manufacturer.

Each of these two forms of coordination—internal and external—has advantages and disadvantages. As Oliver Williamson of the University of California at Berkeley and others have argued, buying things from an outside supplier often requires more coordination than making them internally. To buy tires, General Motors may need to compare many potential suppliers, negotiate contracts and do formal accounting for the money that changes hands. Coordinating the production of tires internally, on the other hand, can often be done less formally and at lower cost, with telephone calls and meetings.

But improved information technology should reduce the costs of both internal and external coordination, much as transportation technology lowered the expense of traveling. When trains and automobiles reduced the difficulty of traveling, more people chose to live in the suburbs rather than in the cities to reap such benefits as extra living space. Similarly, when information technology reduces the costs of a given amount of coordination, companies will choose to buy more and make less. The additional coordination required in buying will no longer be as expensive, and buying has certain advantages. For instance, when General Motors buys tires, it can take advantage of the supplier's economies of scale and pick the best tires currently available from any supplier whenever its needs change. Thus, we expect networks to lead to less vertical integration—more buying



SCANNING OF BAR CODES is one component of the textile industry's Quick Response program. The scans provide information about the contents of a package to each member of the distribution chain, from supplier to retailer. The rapid transmission of data reduces inventory and enables the firms to adjust quickly to demand.

rather than making—and to the proliferation of smaller firms. More electronically mediated alliances (such as the Rosenbluth International Alliance) and an increased use of electronic markets to pick suppliers (such as the airline reservation system) will result.

This argument implies that information technology will help make markets more efficient. Buyers will no longer have to exert great effort to compare products and prices from many different suppliers. Instead an electronic market can easily and inexpensively collect and distribute such information.

These more efficient markets threaten firms whose strategic advantages rest on market inefficiencies. For instance, as Clemons described, when the London International Stock Exchange installed an electronic trading system, the trading floor became virtually deserted within weeks. Trading moved to electronic terminals around the world. The system greatly reduced the costs of matching buyers and sellers. This change, in turn, dramatically reduced the profits of brokers and trading specialists, who previously had had a monopoly on performing this function. The potential decline in profit may explain why many other exchanges still resist electronic trading.

Many other kinds of intermediaries, such as distributors and retailers, are becoming vulnerable as well. For example, consumers can now bypass retail stores entirely by using computer-based systems such as Comp-U-Card and Comp-u-store to buy household goods and services at substantial savings. Electronic markets can also make evaluating product quality easier; we expect that it is only a matter of time before networks contain extensive comments and evaluations from previous buyers, becoming a kind of instantaneous, on-line *Consumer Reports.*

Increasing market efficiency also implies that firms should focus more carefully on the few core competencies that give them strategic advantages in the marketplace. They should buy the additional, more peripheral products and services they need instead of making them. For instance, in the past few years, Ford Motor Company and Chrysler Corporation have significantly increased their proportion of externally purchased components, such as tires and batteries.

Even though information technology can be strategically important, single innovations in information technology are seldom in themselves a source of continuing competitive advantage. For example, American Hospital Supply (now Baxter Healthcare Corporation) won high praise for its early system that let customers place orders electronically without requiring a salesperson. This system made ordering from American Hospital easier than doing so from competitors and reduced the time salespeople had to spend on the clerical aspects of taking an order. But contrary to original expectations, systems like these do not "lock in" customers in the long run. Instead customers eventually seem to prefer electronic systems that provide a choice among several vendors. Similarly, an automatic teller machine system that may once have been a competitive advantage for a bank is now largely a competitive necessity.

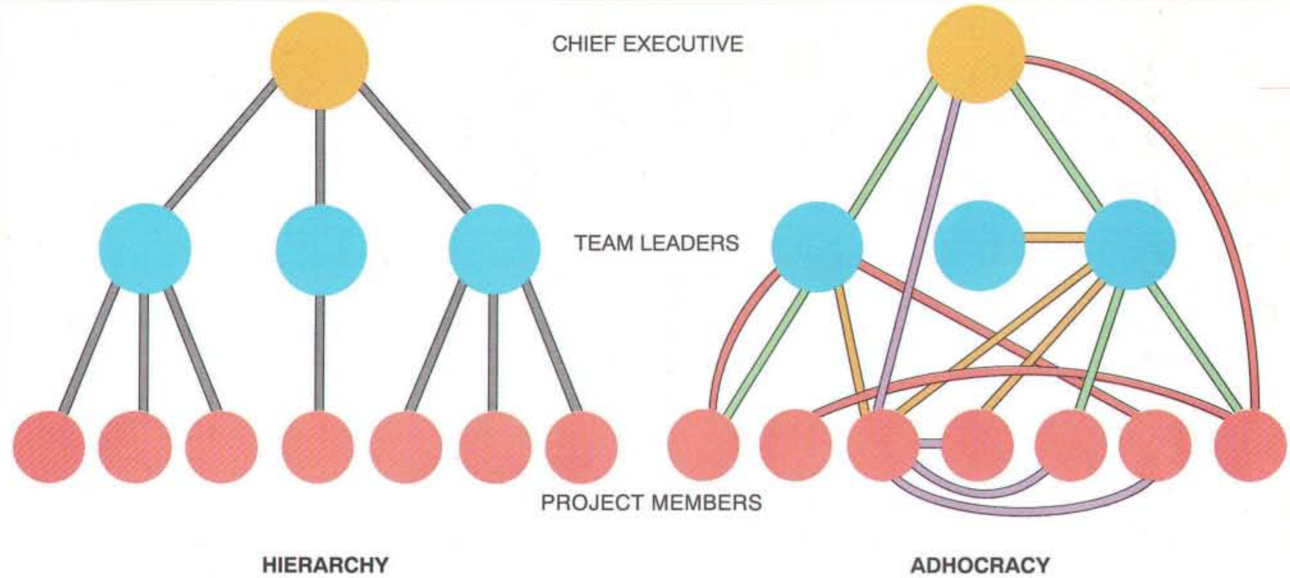
One way to maintain an upper hand is to keep innovating so rapidly that other firms always lag a step behind. Another way, as Clemons has noted, is to use information technology to leverage some other structural advantage. For instance, Barclay deZoete Wedd, a British brokerage firm, continues to benefit from an electronic stock-trading system because the company already controlled the trading of far more stocks than did any of their competitors.

In addition to markets, another coordination-intensive organizational structure likely to become much more com-

Relative Costs for Hierarchies and Markets

Making products in vertically integrated hierarchies usually involves higher production costs than buying them in the market. Buying from an outside supplier allows a company to exploit economies of scale and other production cost advantages. But buying usually requires higher coordination costs; a firm must find a supplier, negotiate contracts and account for payments.

Corporate Structures



mon is what some management theorists call a networked organization, or, more picturesquely, an "adhocracy," a term Alvin Toffler popularized in his book *Future Shock*. This form is already common in organizations such as law firms, consulting companies and research universities. Such organizations and institutions must continually readjust to a changing array of projects, each requiring a somewhat different combination of skills and other resources. These organizations depend on many rapidly shifting project teams and much lateral communication among these relatively autonomous, entrepreneurial groups.

The adhocracy contrasts with the conventional business organization of today: the hierarchy. Hierarchies are common partly because they provide a very economical way of coordinating large numbers of people. In principle, decision makers in a hierarchy can consider all the information known to anyone in the group with much less communication than would be needed if each person communicated with everyone else.

In practice, however, hierarchies have severe limitations. Central decision makers can become overloaded and therefore unable to cope effectively with rapidly changing environments or to consider enough information about complex issues. Furthermore, people at the bottom may feel left out of the decision making and as a result be less motivated to contribute their efforts.

As information technology reduces communication costs, the nonhierarchical structures (such as markets and adhocracies) may help overcome the limitations of hierarchies. For example, because of the large amount of unpredictable lateral communication, the adhocracy is extremely coordination intensive. New media, such as electronic mail, computer conferencing and electronic bulletin boards, can make the coordination easier and, therefore, enable the adhocracy to work much more effectively. Computer networks can help find and coordinate people with diverse knowledge and skills from many parts of an organization.

Moreover, computer-based technologies can transfer information not only faster and more cheaply but also more selectively. These capabilities help to mitigate information overload. Systems now exist to help people find, filter and sort their electronic mail based on topic, sender and other characteristics. Together these new coordination technologies can speed up the "information metabolism" of organizations—the rate at which firms can take in, move, digest and respond to data.

Abundant information poses two potential difficulties for organizational power. Some people worry that managers may become "Big Brothers" who use the information to exert stronger centralized control over those who work for them. Others fear that if power is decentralized throughout the organization, workers might use their newfound power to serve their own narrow interests, leading to organizational chaos.

In fact, neither dark vision has been realized. Instead what appears to be happening is a paradoxical combination of centralization and decentralization. Because information can be distributed more easily, people lower in the organization can now become well enough informed to make more decisions more effectively. At the same time, upper-level managers can more easily review decisions made at lower levels. Thus, because lower-level decision makers know they are subject to spot-checking, senior managers can retain or even increase their central control over decisions.

The changes at Phillips Petroleum Company illustrate this process. Previously, senior managers decided what price to set for petroleum products. These critical decisions depended on the recommendations of staff analysts several levels down. When Phillips Petroleum developed an executive information system, senior managers began to make some of these decisions more directly based on the global information provided by the system. The senior executives soon realized, however, that they could pass on this global information directly to local terminal managers, who could take into account information such as competitors' prices. By decentralizing the pricing decision in this way, the company made sounder, more profitable pricing strategies in each area of the country.

Another way of understanding this

paradoxical effect is to realize that new technology does not just redistribute power. It can provide a sense of more power for everyone. For example, the agents of several insurance companies currently carry laptop computers when they visit the homes of customers. The agents use the computers to fill out applications and to project premiums and benefits. But typically, underwriters at the corporate headquarters require several weeks to review the applications and to issue new policies.

Soon the underwriting rules for certain routine policies will be included in the laptop computer itself. The agent will be able to issue these policies immediately in the customers' homes.

These systems will thus "empower" the agents, who will control the time and place of the policy-acceptance decisions and can make sales immediately. The authority of the central underwriters will increase as well, because the rules they have created will be applied consistently. The underwriters will also be able to devote more time to analyzing interesting and potentially more profitable nonroutine cases.

Information technology not only changes power; it also changes time. On the one hand, time has expanded. Electronic mail, voice mail and facsimile transmissions can be sent or received at any time of day or night, almost anywhere around the globe. Similarly, customers of automatic teller machines and some stock markets can make transactions around the clock. The "work day" has much less meaning, and companies can compete by expanding the times their services are available.

On the other hand, time has contracted. Companies can also compete on speed. For instance, effective coordination can reduce the time needed to develop new products, deliver orders or react to customer requests. Management teams, such as the one at Phillips Petroleum, have information available throughout the management hierarchy, which enables them to react to market conditions much more quickly. Decisions that might have taken days in the past can now be made within hours or minutes.

The changes discussed so far require no great predictive leaps; they are already happening. What will happen as information technology improves even more? What other kinds of organizations might emerge in the globally interconnected world that the technologies make feasible?

One possibility is the increasing importance of "answer networks," networks of experts available to answer questions in different areas. One might go to these services with questions such as "How many bars of soap were sold in Guatemala last year?" or "What are the prospects of room-temperature superconductivity in consumer products by 1995?" The services would include massive data bases and layers of human experts in many different topic areas. Some questions will be easily answerable from information in a data base. Others will be referred to progressively more knowledgeable human experts. Depending on how much one is willing to spend and how quickly one wants the answer, the response might range from a newspaper clipping to a personal reply from a Nobel laureate scientist. Similar but limited services exist today—product hot lines and library reference desks are examples—but computer networks and data bases will make such services much less expensive, much more valuable and, therefore, much more widely used.

Electronically mediated markets can also assemble armies of "intellectual mercenaries" virtually overnight. For instance, there may be a large number of consultants who make their living doing short-term projects over the network. If a manager has a job to be done, such as evaluating a loan or designing a lawnmower, he or she could quickly assemble a team by advertising electronically or by consulting a data base of available people. The data base might contain not only the skills and billing rates of prospective workers but also unedited comments from others who had used their services before. Although consulting firms and advertising agencies sometimes work like this now, pervasive networks will allow teams to be assembled much more quickly, for shorter projects and from many different organizations.

This kind of market for services might be used inside an organization as well. Instead of always relying on supervisors to allocate the time of people who work for them, extensive internal markets for the services of people and groups may exist. Murray Turoff of the New Jersey Institute of Technology has suggested how such a system might work. Someone with a short programming project to be done, for instance, might advertise internally for a programmer. Bids and payments for this internal market could be in real dollars or some kind of point system. The bids from programmers would indicate their skill and availability. The payments that programmers receive would reflect how valuable they had been to other parts of the organization.

Improved technology can also help create decision-making structures that integrate qualitative input from many people. For instance, in making complex decisions, such as where to locate a new plant, the amassing of many facts and opinions is critical. Today companies often make such decisions after incomplete discussions with only a few of the people whose knowledge

AUTOMATIC TELLER MACHINES, once a novelty, are now largely a competitive necessity; single innovations in information technology seldom provide long-term advantages. To remain competitive, firms must keep innovating to stay a step ahead or use existing technology to enhance some other advantage.

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SUBURBS represent a third-order effect of improved transportation technology: with cheap and convenient transportation came "transportation-intensive" structures. Their existence, however, also depended on the American values placed on the importance of home ownership and the moral superiority of rural life. Similarly, the kinds of coordination-intensive structures that will emerge when information becomes freely accessible will depend on the values society finds important. Will the ideals that shaped Boca Raton, Fla., also play a role in future corporate structures?

or point of view might be valuable. In the future, companies may use computer networks to organize and record the issues, alternatives, arguments and counterarguments in graphical form. Then many different people can review and critique the parts of the argument about which they know or care.

For instance, someone in a remote part of the firm might know about plans for a new highway that completely change the desirability of a proposed plant location. As such information accumulates, people can vote on the plausibility of different claims. Then, using all the information displayed in the system, a single person or group can ultimately make the decision.

What will happen as the globally networked society leads to a world in which vast amounts of information are freely available or easily purchased? Clearly, this world will require services, both automated and human, to filter the tremendous amount of information available. In general, as the amount of information increases, people who can creatively analyze, edit and act on information in ways that cannot be automated will become even more valuable.

But what else people will do will depend on the values that are important to them. When trains and automobiles reduced the constraints of travel time, other values became more significant in determining working and living patterns. As Kenneth T. Jackson of Columbia University has documented, for example, American values about the importance of owning one's home and the moral superiority of rural life played a large role in determining the nature of suburbs in the U.S.

Similarly, when the costs of information and coordination are not a barrier to fulfilling people's needs and wants, other values may emerge to shape the workplace and society. The new information technologies will almost certainly help gratify some obvious wants, such as the desire for money. Some of the emerging corporate structures may be especially good at satisfying nonmaterial needs, such as those for challenge and autonomy.

But perhaps these desires are themselves manifestations of some still deeper needs. Psychologists sometimes refer to a need for self-actualization. Others might call this a desire for spiritual fulfillment. To use the new technologies wisely, we will need to think more carefully about what we truly value and how the technology can help us reach our deeper goals.

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Computers, Networks and Education

Globally networked, easy-to-use computers can enhance learning, but only within an educational environment that encourages students to question "facts" and seek challenges

by Alan C. Kay

The physicist Murray Gell-Mann has remarked that education in the 20th century is like being taken to the world's greatest restaurant and being fed the menu. He meant that representations of ideas have replaced the ideas themselves; students are taught superficially about great discoveries instead of being helped to learn deeply for themselves.

In the near future, all the representations that human beings have invented will be instantly accessible anywhere in the world on intimate, notebook-size computers. But will we be able to get from the menu to the food? Or will we no longer understand the difference between the two? Worse, will we lose even the ability to read the menu and be satisfied just to recognize that it is one?

There has always been confusion between carriers and contents. Pianists know that music is not in the piano. It begins inside human beings as special urges to communicate feelings. But many children are forced to "take piano" before their musical impulses develop; then they turn away from music for life. The piano at its best can only be an amplifier of existing feelings, bringing forth multiple notes in harmony and polyphony that the unaided voice cannot produce.

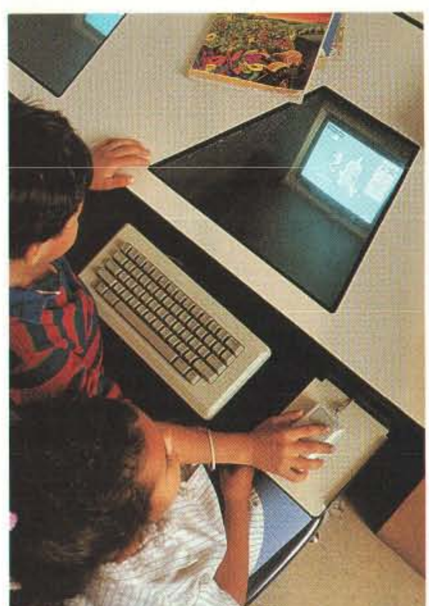
The computer is the greatest "piano" ever invented, for it is the master carrier of representations of every kind. Now there is a rush to have people, especially schoolchildren, "take computer." Computers can amplify yearnings in ways even more profound than can musical instruments. But if teachers do not nourish the romance of learning and expressing, any external mandate for a new "literacy" becomes as much a crushing burden as being forced to perform Beethoven's sonatas while having no sense of their beauty. Instant access to the world's information will probably have an effect opposite to what is hoped: students will become numb instead of enlightened.

ALAN C. KAY has been a fellow of Apple Computer Inc. since 1984. Before joining Apple, he was a founder and fellow of the Xerox Palo Alto Research Center and, later, chief scientist of Atari. One of the pioneers of personal computing, he is the original designer of the overlapping-window user interface and Smalltalk, the first completely object-oriented language. Kay has worked with children for most of his career because, he says, "the media that powerfully shape our ways of thinking must be made accessible as early in life as possible." His interests outside of computing include musical performance and instrument design and "trying to learn more about the world in which we find ourselves." He also plays tennis whenever he can.

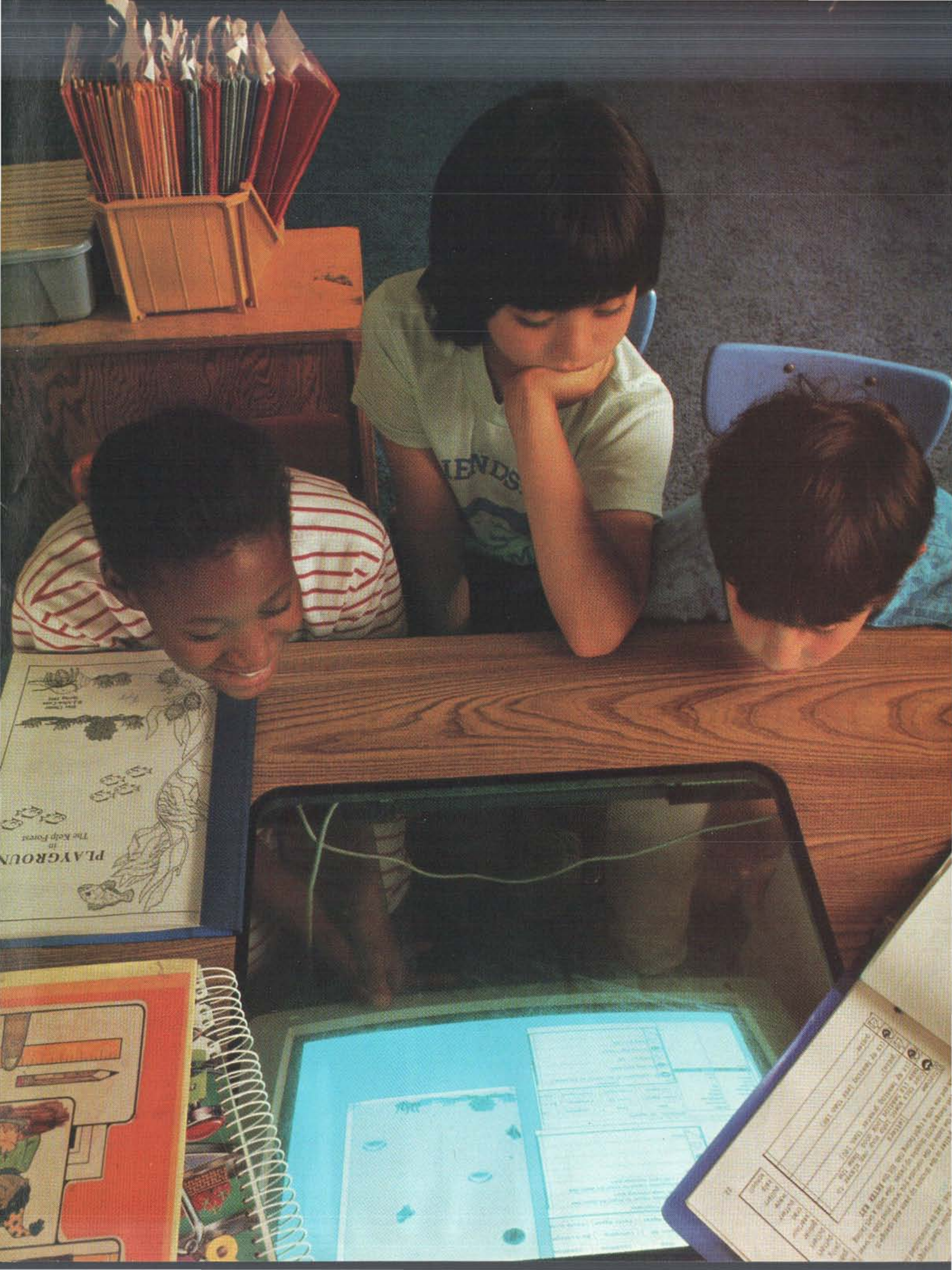
In addition to the notion that the mere presence of computers will improve learning, several other misconceptions about learning often hinder modern education. Stronger ideas need to replace them before any teaching aid, be it a computer or pencil and paper, will be of most service. One misconception might be called the fluidic theory of education: students are empty vessels that must be given knowledge drop by drop from the full teacher-vessel. A related idea is that education is a bitter pill that can be made palatable only by sugarcoating—a view that misses the deep joy brought by learning itself.

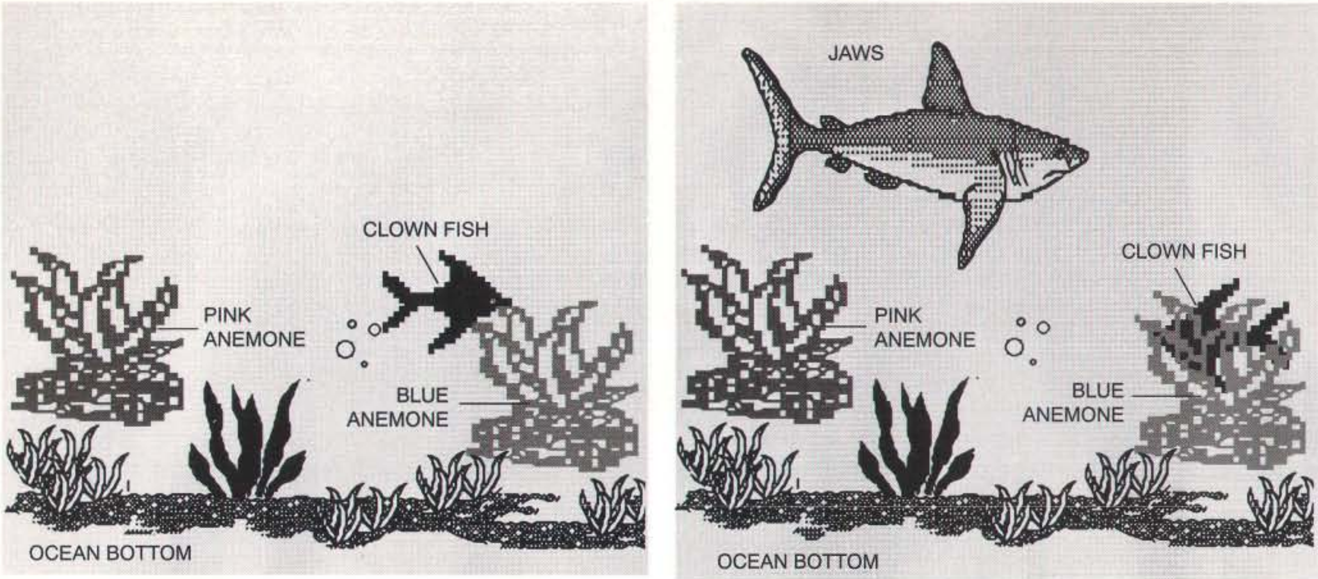
Another mistaken view holds that humans, like other animals, have to make do only with nature's mental bricks, or innate ways of thinking, in the construction of our minds. Equally worrisome is the naive idea that reality is solely what the senses reveal. Finally, and perhaps most misguided, is the view that the mind is unitary, that it has a seamless "I"-ness.

Quite the contrary. Minds are far from unitary: they consist of a patchwork of different mentalities. Jerome S.



STUDENTS at the Open School: Center for Individualization, in Los Angeles, are creating a dynamic simulation of ocean life (*right*) and doing math (*above*) with the help of Macintosh computers, which are set unobtrusively into the desks. In the Open School, which already had a strong curriculum before it obtained computers, the machines do not substitute for teachers. They are thought of as "just another material," like books, paints and clay, that can support the children's activities. In the next few years, notebook-size computers are expected to become available; then children will be able to carry their computers anywhere they go.





CLOWN FISH IS FEATURED in an ocean simulation constructed by nine- and 10-year-olds at the Open School. The fish repeatedly brushes up against an individual sea anemone (*left panel*) to build immunity to its poisonous stings. After immunity is established (*right panel*), the fish can take refuge among the anemone's tentacles whenever a predator (here a shark named Jaws) is near. By constructing simulations, the children learn more about the challenges of being a clown fish and the benefits of symbiosis than they would if they engaged only in more passive activities—such as reading books and observing a fish tank. The author argues that adults, too, learn best when they can test ideas through simulation.

Bruner of New York University has suggested that we have a number of ways to know and think about the world, including doing, seeing and manipulating symbols. What is more, each of us has to construct our own version of reality by main force, literally to make ourselves. And we are quite capable of devising new mental bricks, new ways of thinking, that can enormously expand the understandings we can attain. The bricks we develop become new technologies for thinking.

Many of the most valuable structures devised from our newer bricks may require considerable effort to acquire. Music, mathematics, science and human rights are just a few of the systems of thought that must be built up layer by layer and integrated. Although understanding or creating such constructions is difficult, the need for struggle should not be grounds for avoidance. Difficulty should be sought out, as a spur to delving more deeply into an interesting area. An educational system that tries to make everything easy and pleasurable will prevent much important learning from happening.

It is also important to realize that many systems of thought, particularly those in science, are quite at odds with common sense. As the writer Susan Sontag once said, "All understanding begins with our not accepting the world as it appears." Most science, in fact, is quite literally non-sense. This idea became strikingly obvious when such instruments as the telescope and microscope revealed that the universe consists of much that is outside the reach of our naive reality.

Humans are predisposed by biology to live in the barbarism of the deep past. Only by an effort of will and through use of our invented representations can we bring ourselves into the present and peek into the future. Our educational systems must find ways to help children meet that challenge.

In the past few decades the task before children—before all of us—has become harder. Change has accelerated so rapidly that what one generation learns in childhood no longer applies 20 years later in adulthood. In other words, each generation must be able to quickly learn new paradigms, or ways of viewing the world; the old ways do not remain usable for long. Even scientists have problems making such transitions. As Thomas S. Kuhn notes dryly in *The Structure of Scientific Revolutions*, a paradigm shift takes about 25 years to occur—because the original defenders have to die off.

Much of the learning that will go on in the future will necessarily be concerned with complexity. On one hand, humans strive to make the complex more simple; categories in language and universal theories in science have emerged from such efforts. On the other hand, we also need to appreciate that many apparently simple situations are actually complex, and we have to be able to view situations in their larger contexts. For example, burning down parts of a rain forest might be the most obvious way to get arable land, but the environmental effects suggest that burning is not the best solution for humankind.

Up to now, the contexts that give meaning and limitation to our various knowledges have been all but invisible. To make contexts visible, make them objects of discourse and make them explicitly reshapable and inventable are strong aspirations very much in harmony with the pressing needs and onrushing changes of our own time. It is therefore the duty of a well-conceived environment for learning to be contentious and even disturbing, seek contrasts rather than absolutes, aim for quality over quantity and acknowledge the need for will and effort. I do not think it goes too far to say that these requirements are at odds with the prevailing values in American life today.

If the music is not in the "piano," to what use should media be put, in the classroom and elsewhere? Part of the answer depends on knowing the pitfalls of existing media.

It is not what is in front of us that counts in our books, televisions and computers but what gets into our heads and why we want to learn it. Yet as Marshall H. McLuhan, the philosopher of communications, has pointed out, the form is much of what does get into our heads; we become what we behold. The form of the carrier of information is not neutral; it both dictates

the kind of information conveyed and affects thinking processes.

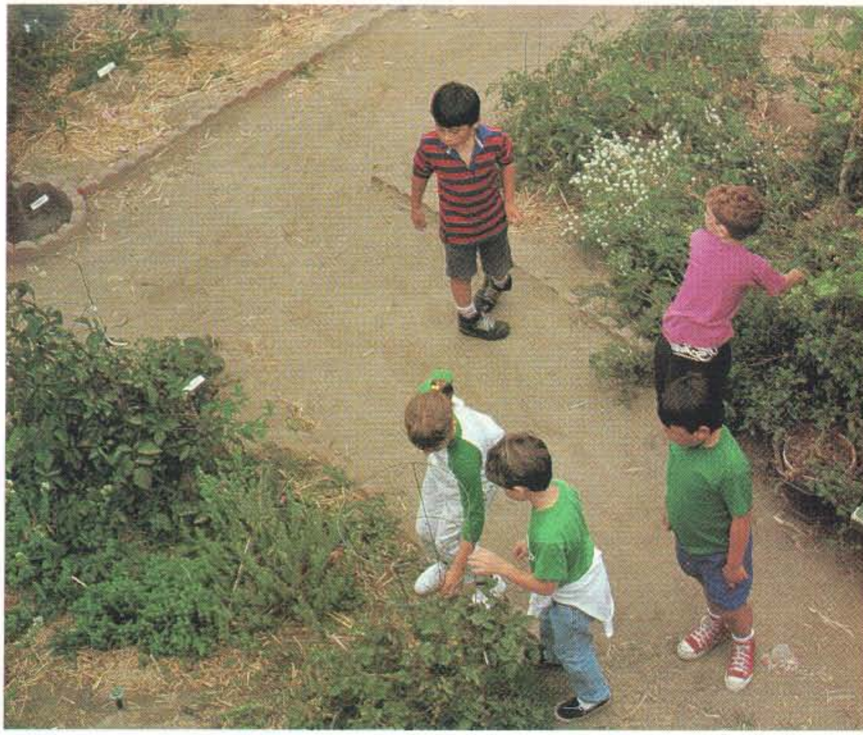
This property applies to all media, not just the new high-tech ones. Socrates complained about writing. He felt it forced one to follow an argument rather than participate in it, and he disliked both its alienation and its persistence. He was unsettled by the idea that a manuscript traveled without the author, with whom no argument was possible. Worse, the author could die and never be talked away from the position taken in the writing.

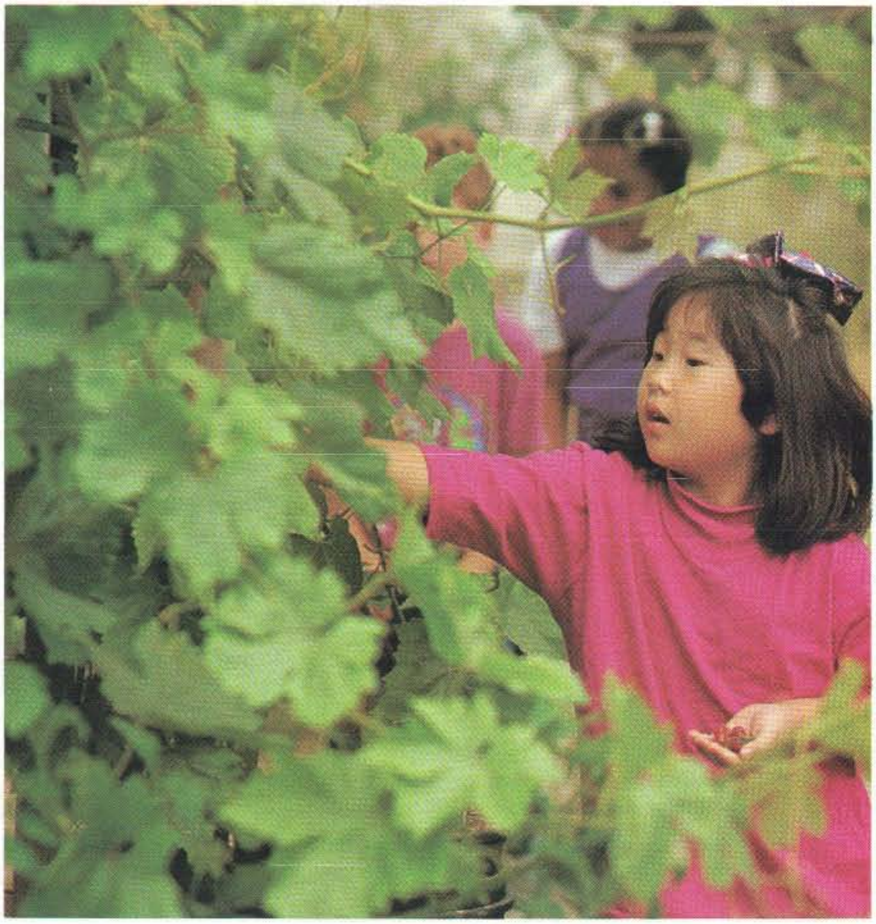
Users of media need to be aware, too, that technology often forces us to choose between quality and convenience. Compare the emotions evoked by great paintings and illuminated manuscripts with those evoked by excellent photographs of the originals. The feelings are quite different. For the majority of people who cannot make such comparisons directly, there is an understandable tendency to accept the substitution as though nothing were lost. Consequently, little protest has been made over replacing high-resolution photographs of great art (which themselves do not capture the real thing) with lower-resolution videodisc images (which distort both light and space even further). The result is that recognition, not reverie, is the main goal in life and also in school, where recognition is the highest act to which most students are asked to aspire.

When convenience is valued over quality in education, we are led directly to "junk" learning. This is quite analogous to other junk phenomena, pale substitutions masquerading for the real thing. Junk learning leads to junk living. As Neil M. Postman of New York University says, whether a medium carries junk is not important, since all media have junk possibilities. But one needs to be sure that media incapable of carrying important kinds of discourse—for example, television—do not displace those that can.

Media can also lure us into thinking we are creating by design when in fact we are just tinkering. Consider the difficulty of transforming clay—a perfectly malleable and responsive substance—into anything aesthetically satisfying. Perfect "debugability," or malleability, does not make up for lack of an internal image and shaping skills. Unfortunately, computers lend themselves to such "clay pushing"; they tempt users to try to debug constructions into existence by trial and error.

Finally, as McLuhan noted, the instant communication offered by today's media leads to fragmentation. Sequence and exposition are replaced by isolated,





WALKWAY through a garden (*top*) outside the Open School was designed by the third graders, who chose a herringbone pattern to ensure easy access to all plots. The children settled on the pattern after creating and debating many models, often with the help of their computers. The garden is part of the Life Lab project, in which children plan, plant, tend and enjoy the fruits of their own garden (*bottom*) as a way of learning about the interaction of living things with the environment.

context-free factoids, often presented simply because they are recent. Two hundred years ago the Federalist papers—essays by James Madison, Alexander Hamilton and John Jay arguing for ratification of the U.S. Constitution—were published in newspapers in the 13 colonies. Fifty years later the telegraph and its network shifted the goals of news from depth to currency, and the newspapers changed in response. Approximately 100 years after that, television started shifting the emphasis of news from currency to visual immediacy.

Computers have the same drawbacks as other media, and yet they also offer opportunities for counteracting the inherent deficits. Where would the authors of the Constitution publish the Federalist papers today? Not in a book; not enough people read books. Not in newspapers; each essay is too long. Not on the television; it cannot deal with thoughtful content. On computer networks? Well, computer displays, though getting better every year, are not good enough for reading extended prose; the tendency is to show pictures, diagrams and short "bumper sticker" sentences, because that is what displays do well.

But the late 20th century provides an interesting answer to the question: transmitting over computer networks a simulation of the proposed structure and processes of the new Constitution. The receivers not only could run the model but also could change assumptions and even the model itself to test the ideas. The model could be hyperlinked to the sources of the design, such as the constitution of Virginia, so that "readers" might readily compare the new ideas against the old. (Hyperlinking extends any document to include related information from many diverse sources.) Now the receivers would have something stronger than static essays. And feedback about the proposals—again by network—could be timely and relevant.

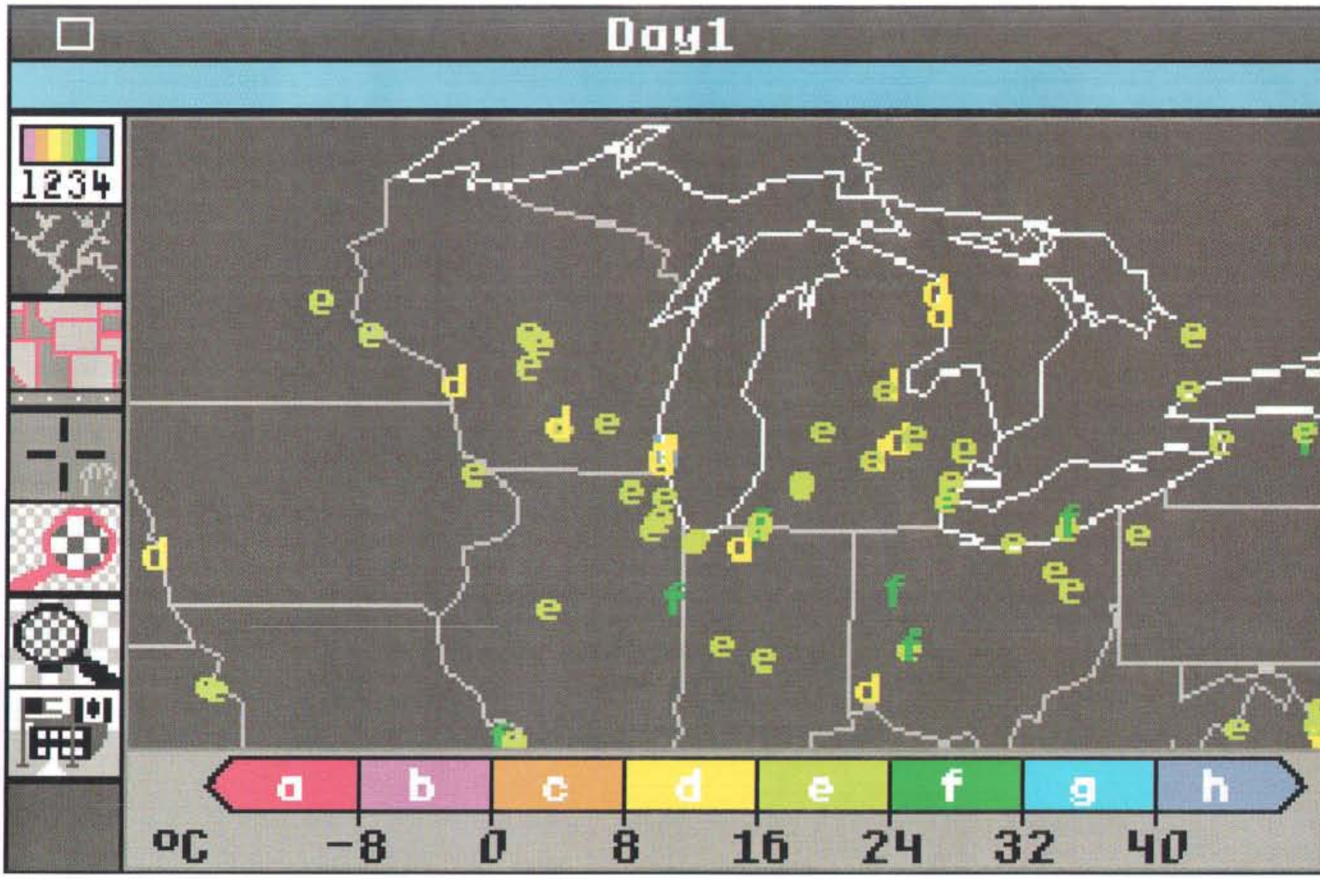
Five years ago, intent on studying firsthand the strengths and weaknesses of computers as amplifiers for learning, my colleague Ann Marion and I, in collaboration with the Open School: Center for Individualization, in Los Angeles, set up a research project called the Apple Vivarium Program. We and the principal, Roberta Blatt, were not trying to improve the already excellent school by introducing technology. We were trying to better understand the value computers might have as supporting media.

MODEL CITY was built by third graders at the Open School after months of planning. Although the children erected the buildings by hand, they turned to their computers for assistance on a number of jobs. For instance, the computers helped the students simulate the formation of smog in their city.

Children are bused in and, as is the case with other busing schools in Los Angeles, are selected by lot so that the racial balance is roughly in accord with that of the city as a whole. Parents have to be interested enough in their children and the school's teaching approach to put their children on the list for consideration. Parental interest and involvement are key factors that have made the school a success. One could even argue that the educational approach in a classroom is not nearly as important as the set of values about learning found in the home. If those exist, almost any process will work, although some may be more enjoyable and enriching than others.

We particularly wanted to investigate how children can be helped to understand that animals, people and situations are parts of larger systems that influence one another. We therefore focused much of our work on the study of biology and ecology. Studies of the design and functioning of large cities also give children an awareness of such complexity. Doreen Nelson of the California Polytechnic Institute has been teaching city design to children for many years; on the basis of her work, our study group introduced a large-scale city-building project for the third graders. We also helped the school develop a major theater program, so the children might see how art and systems work from the inside.

What does it mean to learn about biology as it relates to us and our world? All creatures consist of and are part of many systems that range from the molecular to the planetary. A weak way to approach this romance—in which we are at once part of the scenery, bit



PLOT OF TEMPERATURES in the Great Lakes region of the U.S. is part of an international map created from data collected by students in hundreds of schools. The children took measurements at the same time of day and pooled them through a network. Making such maps is part of the *Weather in Action* unit of the National Geographic Kids Network curriculum. It is also an example of how networks can enhance scientific collaboration—for children as much as for adults.

players, star-crossed lovers, heroes and villains—would be a well-meaning attempt to use books, computers or other representational media as "delivery vehicles." There could be videodiscs showing plant and animal growth, and the students could have network access to data about crop yields, taxonomies of animals and plants, and so forth. But why substitute a "music appreciation" approach for the excitement of direct play? Why teach "science and math appreciation," when the children can more happily (and to better effect) actually create whole worlds?

What is great in biology and humankind's other grand investigations cannot be "delivered." But it can be learned—by giving students direct contact with "the great chain of being," so that they can internally generate the structures needed to hold powerful ideas. Media of all kinds can now be used to amplify the learning experience, whereas before they acted as a barrier to the "good stuff."

The Open School is nothing if not straightforward. Because "things that grow" is the essence of what is called the Life Lab program, the children made a garden, tearing up part of their asphalt playground to get good clean dirt. The third graders, while in the midst of their city-building project, spent months modeling and debating designs for the garden. They ultimately arrived at a practical, child-scaled pattern featuring a herringbone-shaped walkway that puts every plot in reach.

Not surprisingly, the children found that the simulation capability of their computers helped them examine the merits of many different walkway designs. Like modern-day architects, they used the computer to help construct models of their ideas. Teachers Dolores Patton and Leslie Barclay facilitated the process, but it was the children who came up with the ideas.

There are many Life Lab schools in California. Because they are engaged in similar pursuits, they have things to say to one another. For them, networks serve as much more than a conduit for retrieving fixed data; they allow students to develop knowledge of their own collaboratively. For example, it is easy to make one's own weather maps on the basis of simultaneous recordings of temperature and barometric pressure and the like and to argue via network about what the maps mean.

Computer animation can be used to ponder the patterns more readily. A fairly easy inference is that pressure changes seem to go from west to east. Could this have anything to do with the rotation of the earth? The directions of winds are more complicated, since they are more affected by features of the terrain. Do they match up with pressure changes?

We can go still deeper. Children are capable of much depth and attention to quality when they are thinking about questions that seem important to them. Why do animals do what they do? Why do humans do what we do? These are vital issues. Close observation, theories and role-playing help. Reading books about animal behavior helps. The teacher can even explain some ideas of the Nobel laureate Niko Tinbergen, such as the suggestion that animal behavior is organized into modules of innate patterns.

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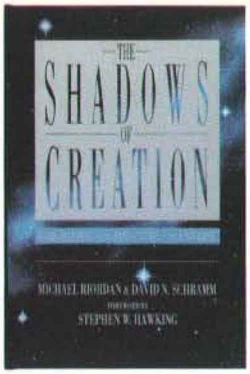

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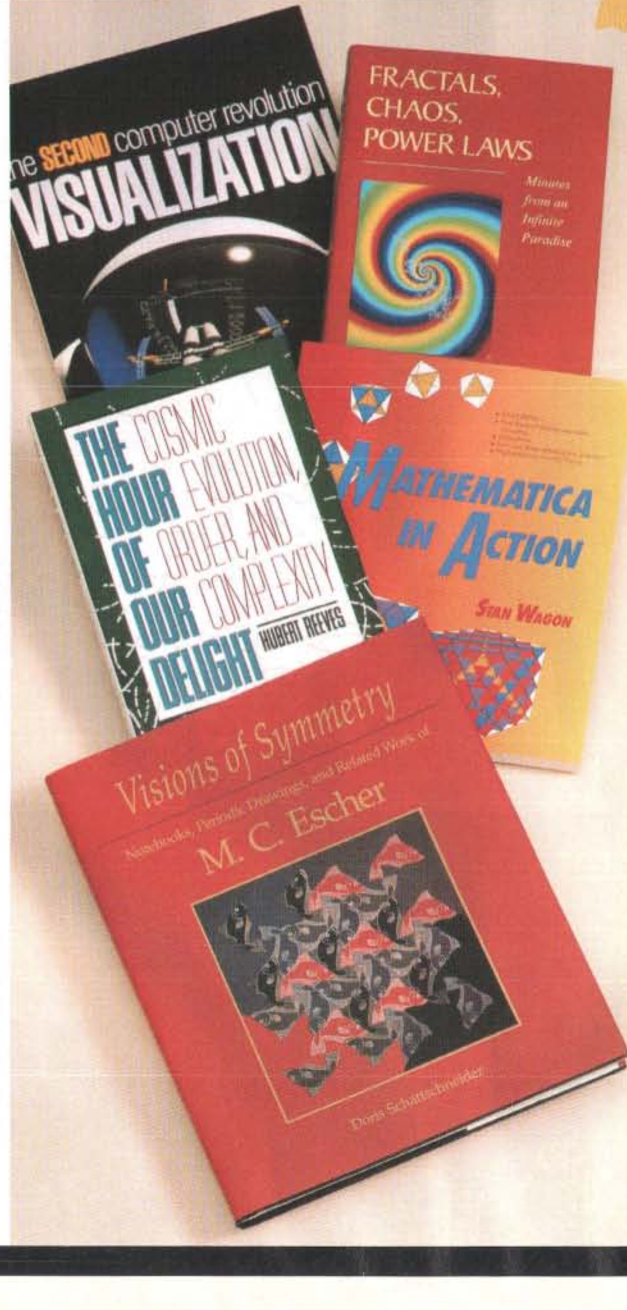

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But these are just words. Now the children can make dynamic models of animal behavior patterns to test Tinbergen's concepts themselves.

Can nine- and 10-year-old children actually capture and understand the mentality of a complex organism, such as a fish? Teacher B. J. Allen-Conn spent several summers learning about intricate ecological relations in the oceans. She searched for ways to express how an individual's behavior is altered by interactions with many other animals. At the same time, Michael Travers, a graduate student from the Media Laboratory at the Massachusetts Institute of Technology who was working with us, built several animal simulations, among them fish behaviors described by Tinbergen. Then Scott Wallace and others in our group turned these various ideas into Playground, a simulation construction kit for children.

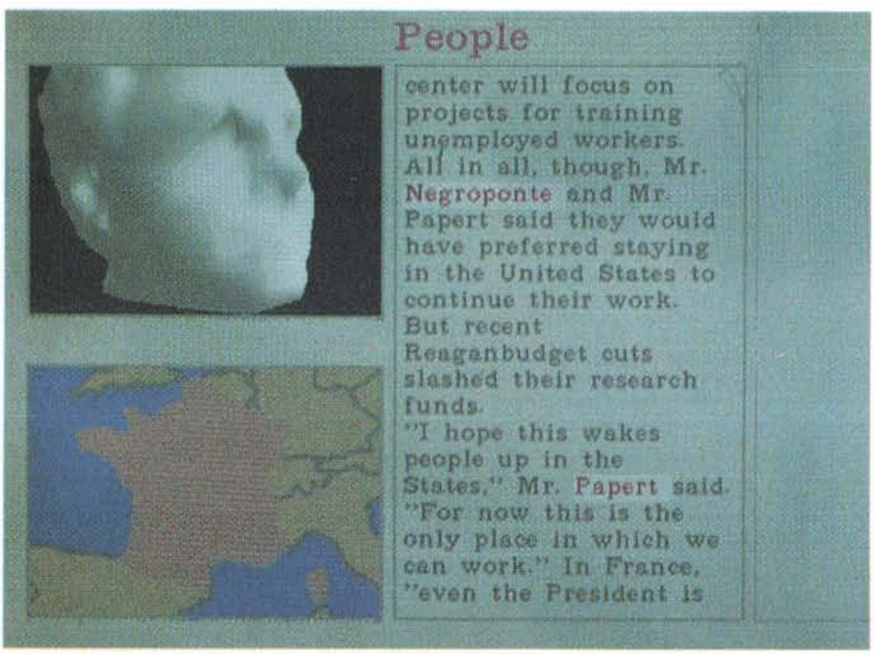
Children are particularly enthralled by the clown fish, which exhibits all expected fishlike behaviors (such as feeding, mating and fleeing from predators) but also displays a fascinating way of protecting itself. It chooses a single sea anemone and gradually acclimates to the anemone's poison over a period of several days. When acclimation is complete, the clown fish has a safe haven where it can hide if a predator comes hunting.

It is fairly easy to build a simple behavior in Playground, and so the children produce simulations that reflect how the fish acts when it gets hungry, seeks food, acclimates to an anemone and escapes from predators. Later they can explore what happens when scripts conflict. What happens if the animal is very hungry yet there is a predator near the food? If the animal is hungry enough, will it start eyeing the predator as possible food? Do the fish as a group fare best when each animal is out for itself, or does a touch of altruism help the species overall?

For an adult, the children's work would be called Artificial Intelligence Programming Using a Rule-Based Expert Systems Language. We researchers and the teachers and children see the dynamic simulations as a way of finding out whether theories of animal behavior apply to the real world.

Computers in the Open School are not rescuing the school from a weak curriculum, any more than putting pianos in every classroom would rescue a flawed music program. Wonderful learning can occur without computers or even paper. But once the teachers and children are enfranchised as explorers, computers, like pianos, can serve as powerful amplifiers, extending the reach and depth of the learners.

Many educators have been slow to recognize this concept of knowledge ownership and to realize that children, like adults, have a psychological need for a personal franchise in the culture's knowledge base. Most schools force students to learn somebody else's knowledge. Yet, as John Holt, the teacher and philosopher of education, once said, mathematics and science would probably be learned better if they were made illegal. Children learn in the same way as adults, in that they learn best when they can ask their own questions, seek answers in many places, consider different perspectives, exchange views with others and add their own findings to existing understandings.



EXCERPT FROM A NEWSCLIP is part of a newspaper tailored to the interests of a single individual; the text was produced several years ago by the software program NewsPeek, which the author and Walter Bender designed when they were at the Massachusetts Institute of Technology. The program is an early prototype for one kind of "agent," a system that can learn a user's goals and retrieve relevant information on the person's behalf. Such agents will one day be essential for navigating through the mass of information that will be available on networks.

Ten years from now, powerful, intimate computers will become as ubiquitous as television and will be connected to interlinked networks that span the globe more comprehensively than telephones do today. My group's experience with the Open School has given us insight into the potential benefits of this technology for facilitating learning.

The first benefit is great interactivity. Initially the computers will be reactive, like a musical instrument, as they are today. Soon they will take initiatives as well, behaving like a personal assistant. Computers can be fitted to every sense. For instance, there can be displays for vision; pointing devices and keyboards for responding to gesture; speakers, piano-type keyboards and microphones for sound—even television cameras to recognize and respond to the user's facial expressions. Some displays will be worn as magic glasses and force-feedback gloves that together create a virtual reality, putting the user inside the computer to see and touch this new world. The surface of an enzyme can be felt as it catalyzes a reaction between two amino acids; relativistic distortions can be directly experienced by turning the user into an electron traveling at close to the speed of light.

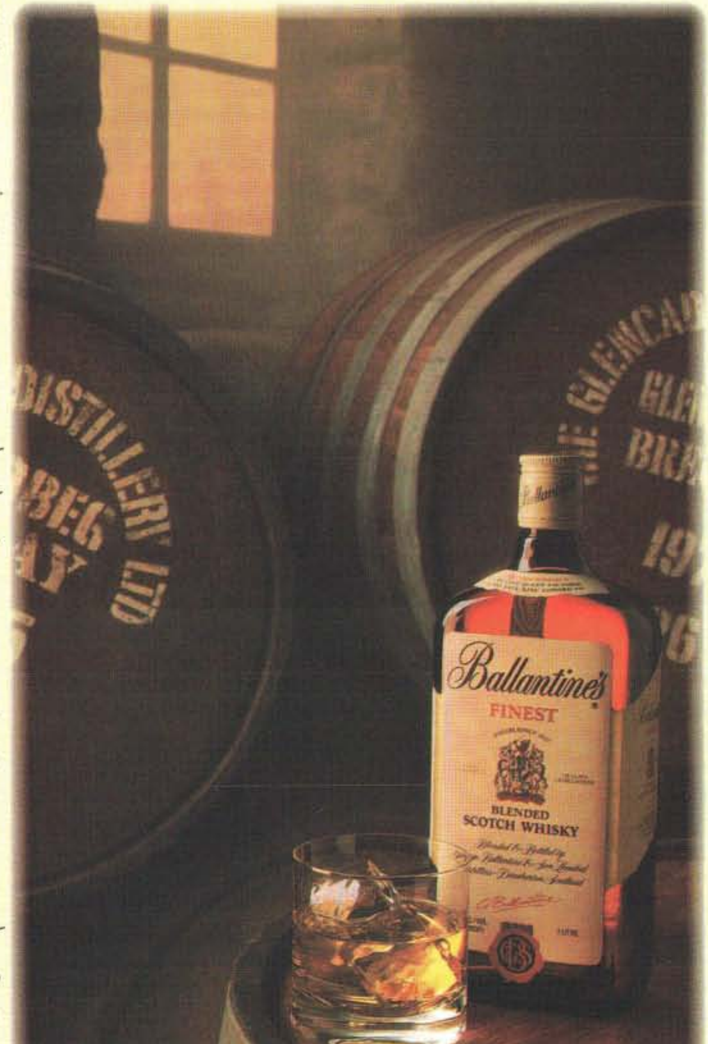
A second value is the ability of the computers to become any and all existing media, including books and musical instruments. This feature means people will be able (and now be required) to choose the kinds of media through which they want to receive and communicate ideas. Constructions such as texts, images, sounds and movies, which have been almost intractable in conventional media, are now manipulatable by word processors, desktop publishing, and illustrative and multimedia systems.

Third, and more important, information can be presented from many different perspectives. Marvin L. Minsky

If We All Aged Half As Well, The World Would Be A Much More Civilized Place.

Some say the secret to the popularity of Ballantine's Finest Scotch is its artful blend of 42 single malt whiskies. Others proclaim the virtues of water, peat or heather, traces of which can be detected in every sip. But all discussions about Scotch must ultimately turn to the oak barrels in which it matures.

Newly distilled single malt Scotch enters the barrel naked, virtually clear, fiery in its potency, but somewhat lacking in manners. Over the years it acquires a golden hue, drawn from the wood itself. Air penetrates the porous surface, whispering hints of the outside world to the budding whisky inside. In turn, evaporation imparts a subtle sweetness to the surrounding air.



When the whisky emerges from its long metamorphosis, it has mellowed considerably. Tempered with soft Scottish water and merged into the Ballantine's Finest blend, each of the single malts confidently introduces itself to your glass, proud of its origin, asserting its flavor with the firm handshake of individual Scotch character.

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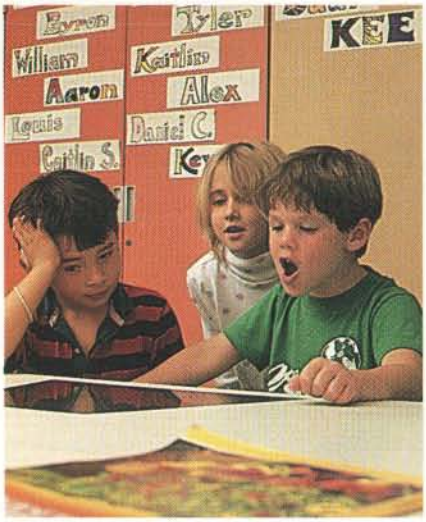

CHILDREN AT A COMPUTER in the Open School are clearly engrossed in their work. If used properly, the author notes, computers can be "powerful amplifiers, extending the reach and depth of the learners."

of M.I.T. likes to say that you do not understand anything until you understand it in more than one way. Computers can be programmed so that "facts" retrieved in one window on a screen will automatically cause supporting and opposing arguments to be retrieved in a halo of surrounding windows. An idea can be shown in prose, as an image, viewed from the back and the front, inside or out. Important concepts from many different sources can be collected in one place.

Fourth, the heart of computing is building a dynamic model of an idea through simulation. Computers can go beyond static representations that can at best argue; they can deliver sprightly simulations that portray and test conflicting theories. The ability to "see" with these stronger representations of the world will be as important an advance as was the transition to language, mathematics and science from images and common sense.

A fifth benefit is that computers can be engineered to be reflective. The model-building capabilities of the computer should enable mindlike processes to be built and should allow designers to create flexible "agents." These agents will take on their owner's goals, confer about strategies (asking questions of users as well as answering their queries) and, by reasoning, fabricate goals of their own.

Finally, pervasively networked computers will soon become a universal library, the age-old dream of those who love knowledge. Resources now beyond individual means, such as supercomputers for heavy-duty simulation, satellites and huge compilations of data, will be potentially accessible to anyone.

For children, the enfranchising effects of these benefits could be especially exciting. The educator John Dewey noted that urban children in the 20th century can participate only in the form, not the content, of most adult activities; compare the understanding gained by a city girl playing nurse with her doll to that gained by a girl caring for a live calf on a farm. Computers are already helping children to participate in content to some extent. How students from preschool to graduate school use their computers is similar to how computer professionals use theirs. They interact, simulate, contrast and criticize, and they create knowledge to share with others.

When massively interconnected, intimate computers become commonplace, the relation of humans to their information carriers will once again change qualitatively. As ever more information becomes available, much of it conflicting, the ability to critically assess the value and validity of many different points of view and to recognize the contexts out of which they arise will become increasingly crucial. This facility has been extremely important since books became widely available, but making comparisons has been quite difficult. Now comparing should become easier, if people take advantage of the positive values computers offer.

Computer designers can help as well. Networked computer media will initially substitute convenience for verisimilitude, and quantity and speed for exposition and thoughtfulness. Yet well-designed systems can also retain and expand on the profound ideas of the past, making available revolutionary ways to think about the world. As Postman has pointed out, what is required is a kind of guerilla warfare, not to stamp out new media (or old) but to create a parallel consciousness about media—one that gently whispers the debits and credits of any representation and points the way to the "food."

For example, naive acceptance of on-screen information can be combated by designs that automatically gather both the requested information and instances in which a displayed "fact" does not seem to hold.

An on-line library that retrieves only what it is requested produces tunnel vision and misses the point of libraries; by wandering in the stacks, people inevitably find gems they did not know enough to seek. Software could easily provide for browsing and other serendipitous ventures.

Today facts are often divorced from their original context. This fragmentation can be countered by programs that put separately retrieved ideas into sequences that lead from one thought to the next. And the temptation to "clay push," to create things or collect information by trial and error, can be fought by organizational tools that help people form goals for their searches. If computer users begin with a strong image of what they want to accomplish, they can drive in a fairly straightforward way through their initial construction and rely on subsequent passes to criticize, debug and change.

If the personally owned book was one of the main shapers of the Renaissance notion of the individual, then the pervasively networked computer of the future should shape humans who are healthy skeptics from an early age. Any argument can be tested against the arguments of others and by appeal to simulation. Philip Morrison, a learned physicist, has a fine vision of a skeptical world: "...genuine trust implies the *opportunity* of checking wherever it may be wanted.... That is why it is the evidence, the experience itself and the argument that gives it order, that we need to share with one another, and not just the unsupported final claim."

I have no doubt that as pervasively networked intimate computers become common, many of us will enlarge our points of view. When enough people change, modern culture will once again be transformed, as it was during the Renaissance. But given the current state of educational values, I fear that, just as in the 1500s, great numbers of people will not avail themselves of the opportunity for growth and will be left behind. Can society afford to let that happen again?

FURTHER READING

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TOWARD A THEORY OF INSTRUCTION. Jerome S. Bruner. Harvard University Press, 1966.

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AMUSING OURSELVES TO DEATH: PUBLIC DISCOURSE IN THE AGE OF SHOW BUSINESS. Neil Postman. Viking Penguin, 1985.

THE RING OF TRUTH: AN INQUIRY INTO HOW WE KNOW WHAT WE KNOW. Philip Morrison and Phylis Morrison. Random House, 1989.

Computers, Networks and Public Policy

The road to the global village is a bumpy one. As computing and communications technologies fuse, they create ways to express ideas, generate knowledge and share information. The new technologies also redefine time and place in a manner that can confound the traditional legal concepts of property, ownership, originality, privacy and intellectual freedom. Government must address such issues, and it must also build a framework of policy that enables the economic and intellectual opportunities of the emerging technologies to be realized.

In the following three articles, Senator Al Gore, an advocate of government support for computer "data superhighways," Anne W. Branscomb, a prominent legal authority, and Mitchell Kapor, software pioneer and the founder of Lotus Development Corporation, explore these issues.

Infrastructure for the Global Village

A high-capacity network will not be built without government investment

by Al Gore

New technologies that enhance the ability to create and understand information have always led to dramatic changes in civilization. The printing press unleashed the forces that led to the birth of the modern nation state. It made possible the widespread distribution of civic knowledge that enabled the average citizen to affect political decisions.

Now come distributed networks connecting a myriad of computers, ranging from megaflop machines and workstations to desktop and personal laptop units. All are becoming less expensive in each successive generation that emerges. There is no longer any doubt that such machines will reshape human civilization even more quickly and more thoroughly than did the printing press. Gutenberg's invention, which so empowered Jefferson and his colleagues in their fight for democracy, seems to pale before the rise of electronic communications and innovations, from the telegraph to television, to the microprocessor and the emergence of a new computerized world—an information age.

As in the past, original thinking is required to develop a system that will enable our civilization to make the most sensible use of this potent technology. There are valid concerns that computer networks threaten the privacy and personal freedom of individuals. There are equally valid worries that existing laws do not adequately protect the rights and liberties of computer users to express themselves in the new medium.

Even so, such concerns should not—and indeed, probably cannot—halt the sweeping changes that are already taking place. Just as information spewing forth from the printing press was soon protected in democratic states by a fair and workable legal and ethical code, so, too, a new body of common law is being built to cope with the new medium of the computer network. Rather than holding back, the U.S. should lead by building the information infrastructure, essential if all Americans are to gain access to this transforming technology.

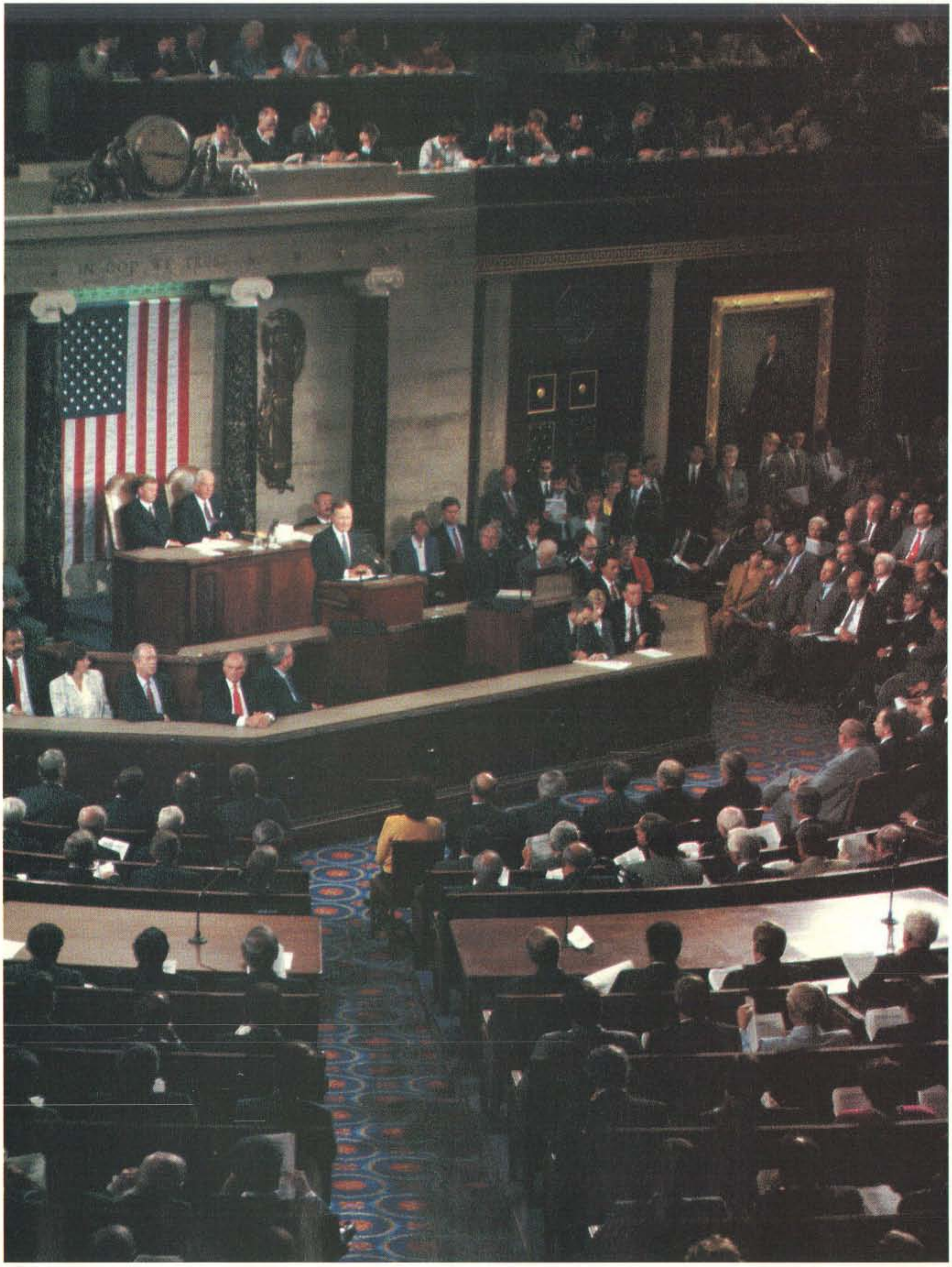
The unique way in which the U.S. deals with information has been the real key to our success. Capitalism and representative democracy rely on the freedom of the individual, so these systems operate in a manner similar to the principle behind massively parallel computers. These computers process data not in one central unit but rather in tiny, less powerful units distributed throughout the computer.

Capitalism works on the same principle. People who are free to buy and sell products or services according to their individual calculations of the costs and benefits of each choice process a relatively limited amount of information but do it quickly. When millions of individuals process information simultaneously, the aggregate result is incredibly accurate and efficient decisions.

Similarly, representative democracy relies on the still revolutionary assumption that the best way for a nation to make political decisions is for all its citizens to process the information relevant to their lives and to express their conclusions in free speech and in votes that are combined with those of millions of others to guide the system as a whole. Communism, by contrast, attempted to bring all the information to a large and powerful central processor, which collapsed when it was overwhelmed by ever more complex information.

Computers are providing people all

AL GORE was elected to the U.S. Senate in 1984, after serving eight years in the House of Representatives as a congressman from Tennessee. A 1969 graduate of Harvard University, he also attended Vanderbilt University Divinity School and Vanderbilt Law School. Gore is chairman of the subcommittee on Science Technology and Space of the Commerce, Science and Transportation Committee. He also serves on Armed Services, Rules and Joint Economic committees. Gore is the author of the High Performance Computing Act of 1990, which would create high-speed fiber-optic computer networks, and has written legislation to encourage the development of high-definition television.



CONGRESS must formulate the policies that are crucial to realizing the potential of the information age. Just as the interstate highway system was built with federal funds, so too will high-speed networks require federal seed capital.

over the U.S. with the ability to process information and to use their creativity to challenge the world around them in ways never before imagined. More and more, computers are replacing telephones; more and more, computers are able to communicate as well as calculate. To realize the full benefit of the information age, we need to take the next step: high-speed networks must be built that tie together millions of computers, providing capabilities that we cannot even imagine. Consider supercomputers. Although they are far more valuable than their weaker predecessors, they cannot be effectively linked together over existing networks.

In laboratories across our country, scientists and researchers armed with powerful supercomputers are using them to design more effective medicines, safer aircraft and automobiles and more efficient products. Scientists studying the earth's environment can produce complex climate models to help understand global warming and other critical atmospheric trends.

Suppose that we had a national "colaboratory" linking teams at different geographic locations so that researchers could work together on projects involving computational science. Suppose that a scientist or an engineer designing a product could immediately transfer a design to the manufacturer, who in turn could transfer it instantly to computer-operated machines ready to turn the idea into reality. The benefits, both intellectual and economic, would be phenomenal.

There have been advances in networking technology. We have the technical know-how to make networks that would enable a child to come home from school and, instead of playing Nintendo, use something that looks like a video game machine to plug into the Library of Congress. It could be possible to gain access to the most powerful supercomputers in our nation from every PC in America—and to gain access to digital libraries, another key part of the national information infrastructure we need.

It used to be that a nation's transportation infrastructure determined success in international economic competition. Nations with deep-water ports did better than nations unable to exploit the technology of ocean transportation. Canals, railroads, highways, water and sewer systems—the list is a long one—were infrastructure investments found, through experience, to provide tremendous leverage for improving a nation's competitiveness.

Today transportation is less important compared with other factors, such as the ability to move information and to increase the value of this information. At the same time, however, we are confronted with massive and rapidly multiplying quantities of information. We are forced to deal with what I call "exformation"—accumulated surpluses of data that we know exist but are outside our conscious awareness.

Fields of specialization are becoming narrower and narrower as the amount of information continues to explode, doubling every six months in some disciplines. In a sense, we have automated the process of gathering information without enhancing our ability to absorb its meaning.

To realize the full benefit of the information age, high-speed networks that tie together millions of computers must be built.

Our current national information policy resembles the worst aspects of our old agricultural policy, which left grain rotting in thousands of storage silos while people were starving. We have warehouses of unused information "rotting," while critical questions are left unanswered and critical problems are left unsolved. For example, the *Landsat* satellite is capable of taking a complete photograph of the entire earth's surface every two weeks. It has been operating for nearly 20 years. Yet more than 95 percent of those images, which might be invaluable to farmers, environmental scientists, geologists, educators, city planners and businesses, have never been seen by human eyes.

Luckily, just as we confront this fantastic problem of so-called exformation, all these silos filled with "rotting data," we see the appearance of the supercomputer. These machines promise the ability to configure or organize information into a form easy for us to absorb. They can search through vast fields of data to find those bits that have special relevance at the moment.

But first we must build a way to use it effectively. Typically, software development follows hardware development, and policy lags behind both. Yet it is policy that can determine whether we reap the benefits of this new technology. In too many cases, we have mastered the technology but failed to muster the political commitment and the appropriate policies.

Federal policies can make a difference in several key areas of the computer revolution. The U.S. Defense Advanced Research Projects Agency (DARPA), the National Aeronautics and Space Administration, the National Science Foundation and the Department of Energy have all spent millions of dollars developing the next generation of supercomputers. It is safe to say that without federal seed money, Cray Research and other American firms would not now dominate the world market for supercomputers.

The funds from those agencies have also built today's research computer networks, such as NSFNET, and underwritten the development of software for top-of-the-line machines. Additional federal research funding is also needed to develop easy-to-use applications for supercomputers and networks (especially in industry and medicine) and to train people in computational science. The massive amounts of data in our information silos, much of it in electronic form, could be made available to researchers over networks. But resources are needed to put the data in a useful format and to catalogue and distribute them.

Most important, we need a commitment to build the high-speed data highways. Their absence constitutes the largest single barrier to realizing the potential of the information age. Present policy, which is based on copper-wire networks, is hindering deployment of the new fiber technology. There is a policy gridlock—some say a "graphic jam"—because the interests that built and still run our existing infrastructure resist changes that might intensify competition.

Other countries, including not only advanced nations such as Japan and Germany but also many countries in the developing world that are just now building a universal telephone system, do not have this problem. If we do not break the communications gridlock, our foreign competitors could once again reap the benefits of U.S. technology while we remain mired in the past.

The most effective way to break the stalemate would be to show the American people what fiber-optic networks could offer them. Most Americans are only vaguely familiar with even existing networks, yet they rely on networks every day. Everyone, from shoppers at the checkout counter to consumers making a withdrawal from an automated teller machine, is dealing with a computer through a network.

Thousands of researchers now use megabit-per-second networks to communicate with computers a continent away. A few hundred people, exemplified by Robert E. Kahn, president of

the Corporation for National Research Initiatives, are building even faster, gigabit networks to link supercomputers, allowing two, three or more supercomputers to work together as one.

Slower networks that operate at 45 megabits a second or less, like NSFNET, are being used by more than half a million researchers, educators and students at colleges, universities and federal and private laboratories to communicate with their colleagues, to access data bases and to collect data from remote instruments. Several high-tech enterprises, such as IBM and AT&T Bell Laboratories, also depend on such networks. Banks and other financial institutions, many factories and other businesses now rely on networks that operate in the range of 50,000 to 100,000 bits per second to exchange electronic mail, financial transactions, stock quotations and other types of information.

Services like Prodigy, GEnie and CompuServe are now in use in almost half a million homes. Children can use "electronic encyclopedias" to finish their term papers, and their parents can keep up with the news, check bank balances and get consumer tips. Hundreds of schools are linked by low-speed (1,200- or 2,400-bit-per-second) networks, such as Kids' Net, that allow students to exchange electronic mail.

Networks thousands or even millions of times faster would offer greater benefits. Today a child can go to a library and use a computer to get the title of a book. A faster network would bring the book to the child at home, pictures and all. But how do we get there? It is estimated that more than $100 billion of private investment would be needed to connect optical fiber to every home, office, factory, school, library and hospital. Unfortunately, the onslaught of technology is causing fierce competition between once separate entities in telecommunications. The telephone companies want to transmit entertainment; the cable carriers are asking to get into the communications business. And businesses are turning to satellite communications carriers or installing private fiber-optic networks.

All are regulated by vague, outdated, conflicting, constantly changing government telecommunications policies. The result is that the private sector hesitates to jump in and make the investment. We face the classic "chicken and egg" dilemma. Because there is no network, there is no apparent demand for the network; because there is no demand, there is no network.

Consider the interstate highway system. It made sense for a postwar America with lots of new automobiles clogging crooked, two-lane roads. But who was going to pay for it? There was no private business that could afford it and no entrepreneur convinced it was worth it. Similarly, the private sector cannot afford to build the high-speed computer network we need and may not even be convinced of its value.

But, like the interstate highway system, once this network is completed, the demand for its use will skyrocket. We are already seeing private and public concerns building feeder networks that, just as state roads feed into the interstate highways, could make the network more effective. More than 2,000 separate networks make up the Internet, the largest national research network. The amount of traffic is growing at the rate of 10 percent a month.

If we do not break the communications gridlock, our competitors could once again reap the benefits while we remain mired in the past.

For almost 15 years, I have been working to change federal policy so that as a nation we will invest in the critical infrastructure of information superhighways. I have fought for funding for the Internet and its successor, the National Research and Education Network (NREN), which will be almost 100 times faster. Its development costs, about $390 million in federal funds over the next five years, represent less than 1 percent of federal research and development expenditures, yet this network could greatly enhance the productivity and value of the other 99 percent of the research and education dollars we spend.

The national network represents a demonstration project that should build public support and influence public policy. I see it as an electronic battering ram to knock down obsolete policies and outdated skepticism. Already the national network as an idea is serving as a catalyst for action by schools and universities, businesses and research centers and even state and local governments.

Adequate federal investment and leadership will give us the power to leverage the millions of dollars into something greater than the sum of its parts. Federal leadership is needed to provide direction and coordination. Federal dollars represent an initial, rather than an ongoing, investment, intended to spark the development that will create the demand for this network as a commercial enterprise.

The "demonstration effect" of the national network will rapidly develop enormous demand for the new information services its high capacity will make possible. It will link the hundreds of computer networks, operated by state and local governments, nonprofit and for-profit corporations, universities and others, to a federally funded "backbone," capable of transmitting billions of bits of data per second.

Without federal funding for this national network, we would end up with a balkanized system, consisting of dozens of incompatible parts. The strength of the national network is that it will not be controlled or run by a single entity. Hundreds of different players will be able to connect their own networks to this one.

The potential benefits of a high-speed network are so obvious and so great that a strong, broad coalition has formed in support. The research and education community, the telecommunications industry, the computer industry and other high-tech industries are all enthusiastic.

But although there is much agreement on the need for the national network, there is still controversy over the next step, the creation of a commercial, ubiquitous, fiber-optic system that can reach into almost every American home. Various sectors of the communications industry—the long-distance telephone companies, the regional Bell operating companies, the cable companies—each want a central role.

It will be up to federal and state policymakers to determine how best to build a universal, high-speed network, to reconcile the competing corporate interests and to create a network that maximizes the benefits enjoyed by all Americans. Given the pace at which networking technology is changing, our efforts will demand more than just vision, leadership and commitment. Flexibility and a willingness to change the details of the plan while constantly moving forward will be required.

Building the national network will be only the first step. That done, we could focus on a telecommunications policy that would resolve the telephone-cable debate, decide what the Baby Bells can and cannot do and confront the challenge presented by other telecommunications issues. We cannot afford to remain deadlocked. The alternative is to wait until other nations show us how to take advantage of this technology—and they will. We must move first.

Common Law for the Electronic Frontier

Networked computing challenges the laws that govern information and ownership

by Anne W. Branscomb

"Cyberspace," says John P. Barlow, computer activist and co-founder of the Electronic Frontier Foundation, "remains a frontier region, across which roam the few aboriginal technologists and cyberpunks who can tolerate the austerity of its savage computer interfaces, incompatible communications protocols, proprietary barricades, cultural and legal ambiguities, and general lack of useful maps or metaphors."

It looks much the same to the legal profession. As networks become less the toys of the console cowboys and more ubiquitous in the daily lives of ordinary computer users, a new breed of lawyers is trying to adapt existing laws to the electronic frontier.

The behavior of computer users in cyberspace, a term for electronic space coined by science fiction writer William Gibson, confounds the carefully honed skills of lawyers to make sense of the morass of new uses of information technology. The electronic environment of computer networks is marked by versatility, complexity, diversity and extraterritoriality. All these characteristics pose challenges to the laws that govern generating, organizing, transmitting and archiving information.

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Today the exchange of information in a network can defy efforts to stop distribution by the very speed with which the deed is accomplished via satellites and optical fibers. In 1988 it took only a matter of hours for the Worm, a rogue computer program, designed by Cornell University graduate student Robert T. Morris, Jr., to circulate through and disable the Internet, the network used by scientists.

The ease with which electronic impulses can be manipulated, modified and erased is hostile to a deliberate legal system that arose in an era of tangible things and relies on documentary evidence to validate transactions, incriminate miscreants and affirm contractual relations. What have been traditionally known as letters, journals, photographs, conversations, videotapes, audiotapes and books merge into a single stream of undifferentiated electronic impulses.

The complex environment and fluid messages make it difficult to determine which version of a document or electronic envelope is the draft or review or "published" copy. The diversity of inputs and outputs also makes it difficult to determine who is author, publisher, republisher, reader or archivist.

Under the 1976 revision of the Copyright Law, one must assume that any original work is protected by an unpublished copyright until published. Consequently, when precisely a work is published and under what proviso it is released are matters of considerable legal interest. Is the electronic record a copyrightable "writing"? If so, by an individual or a group? Suppose some members wish to extract portions of the conversation and transmit them to others. Would that constitute fair use or misuse?

Thus, the information industry, which has thrived on a convenient arrangement between vested interests of authors, publishers and libraries, is now confronting a different economic environment. Computer users have greater freedom to reach out and draw from a digital environment chunks of data in different forms. It is difficult to sort out who is entitled to compensation or royalties from which use of data. Moreover, when a distributed network has multiple participants, it will be more complicated to determine who is entitled to claim recompense for value added.

Lawyers, for whom legal jurisdiction involves the statutory reach of persons residing within certain boundaries, are further confounded by the extraterritoriality (or nonterritoriality) of cyberspace. Electronic communities abound as nodes tied together in a network, be they independent computer bulletin boards or information network providers such as CompuServe, Prodigy Services Company or the Electronic Information Exchange System (EIES).

The earliest global networks, such as the Society for Worldwide Interbank Financial Telecommunication (SWIFT), a system that transfers funds electronically, operate under very stringent rules to which member banks subscribe when entering the system. University network services are scurrying to set up their own codes of conduct in the aftermath of the Internet Worm. How these codes of conduct will mesh with local, state and national laws will prove challenging.

A dialogue held on the Whole Earth 'Lectronic Link (WELL), a computer network operated out of Marin County, Calif., by Stewart Brand of *Whole Earth Catalog* fame, suggests that "computer crackers" will push the outer limits of network security as long as any barrier exists to the free flow of information. A recent revolt of Prodigy subscribers protesting censorship of electronic messages indicates that users want more voice in determining the rules under which they will participate.

Yet what information should be free? Weather forecasts, perhaps news of impending disasters, epidemics, pests, volcanic eruptions? It is inconceivable that we should contemplate a society in which everybody must pay a meter to learn that a hurricane is on the way. But as more and more information is provided by the private rather than the public sector, the line between what is public and what is private blurs.

Moreover, the demarcation between public and private seems to change

constantly. What was yesterday freely obtainable (network sporting events) comes today on a pay-as-you-go basis (on cable channels). Indeed, one obstacle to networked videotex services has been a reluctance of consumers to pay for information in electronic form when it is available in printed form at lower cost.

The privatization and commercialization of information do not sit well with computer hackers, who look on computer networks as an open, sharing society in which the skilled contribute to the welfare of the cooperative. Yet, like pioneers on the Western frontier, they are confronted by those who wish to fence in their private domains.

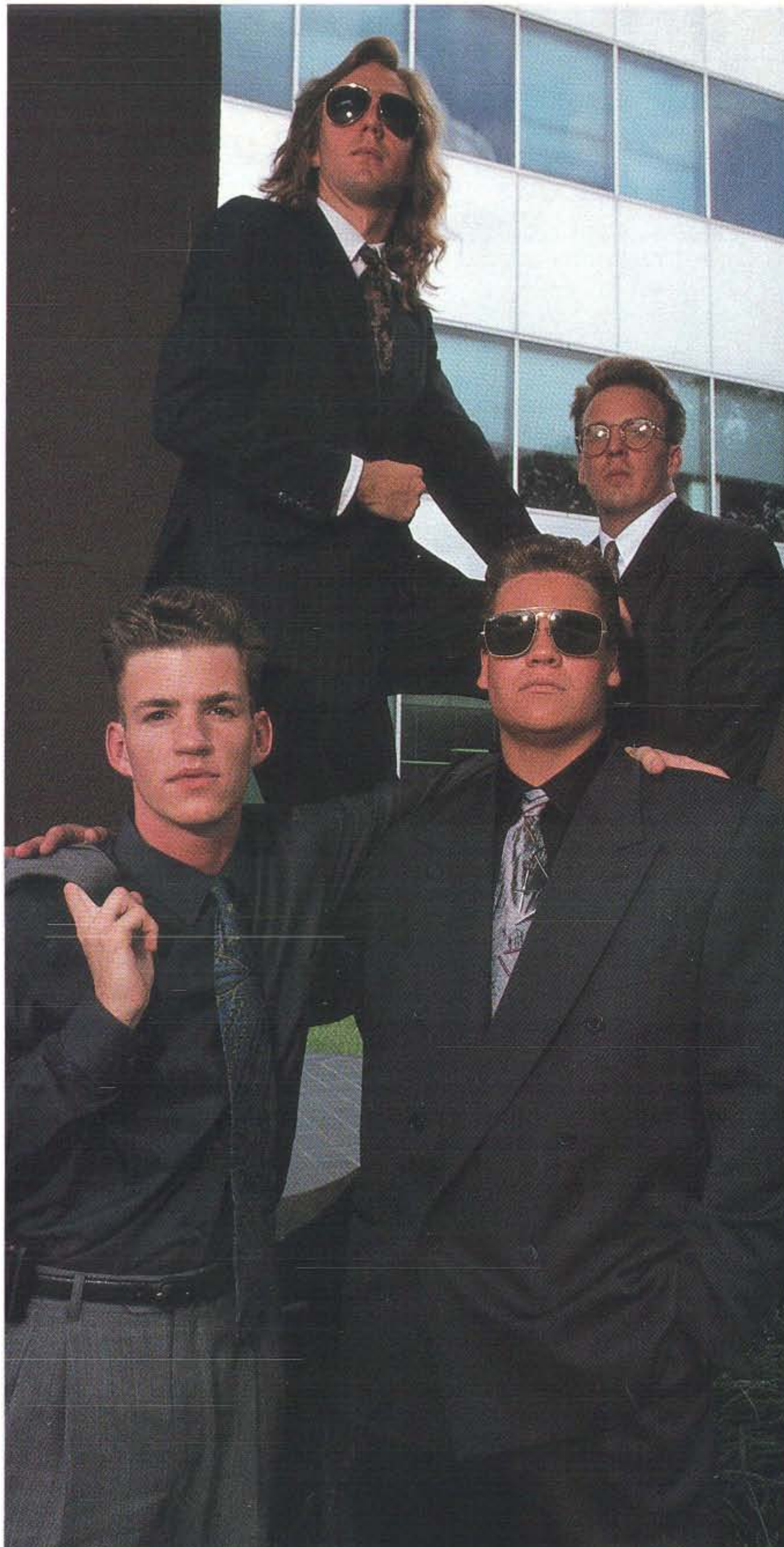
Many computer professionals, for example, have objected to the proprietary control of user interfaces, which programmers need to design compatible and sometimes competitive products. One such group, known as the nuPrometheus League (for the Titan who stole fire from the gods and gave it to humankind), distributed some of the source code of Apple Computer's Macintosh to a variety of computer professionals.

The distribution was apparently a protest against aggressive litigation Apple had instigated against Hewlett-Packard Company and Microsoft Corporation. Apple claimed copyright infringement of its source code on the grounds that software sold by the defending companies appropriated the "look and feel" of its user interface.

The letter accompanying the distribution of the source code was signed "nuPrometheus League (Software Artists for Information Dissemination)" and stated: "Our objective at Apple is to distribute everything that prevents other manufacturers from creating legal copies of Macintosh. As an organization, the nuPrometheus League has no ambition beyond seeing the genius of a few Apple employees benefit the entire world, not just dissipated by Apple through litigation and ill will."

Apple management, which had once encouraged the sharing of software on floppy disks to encourage the use of its computers, promised to prosecute "to the full extent of the law." It declared that those in possession of the code were recipients of stolen property and could be prosecuted under federal laws that prohibit mailing stolen property across state lines.

But U.S. law also has traditionally recognized that much information is freely available for all the world to take and develop as a shared resource. Indeed, the recent Supreme Court deci-



HACKERS from a group called the Legion of Doom were arrested for entering a computer owned by BellSouth. Now four "legionnaires"—Scott Chasin, Chris Goggans, Kenyon Shulman and Robert Cupps (*left to right*)—have formed a company, Comsec Data Security, to help private business fend off intrusion.

sion of *Feist Publications* v. *Rural Telephone Service Company* confirms that the concept of shared information is alive and well.

In this case, an independent telephone company refused to license the use of its telephone directory to Feist Publications, which packaged wider-area directories. So Feist extracted the numbers, claiming they were facts that were not susceptible to copyright protection.

The Supreme Court agreed, putting to rest the labored efforts of a long line of lower courts that attempted to craft a "sweat of the brow" theory to cover the substantial investment made by data base providers in gathering, processing, packaging and marketing their information products.

The application of intellectual property concepts to data bases may become more complex as a result of the Feist decision. Under the copyright rubric, only original expression may be copyrighted, not facts or ideas. Computers can scan pages of data, and, presumably, as long as they do not copy the exact organization or presentation or the software programs used to sort the information, they may not be infringing the copyright of the "compilation," the legal hook on which data bases now hang their protective hats.

Unless Congress or the states clarify what in a data base can be protected, information providers will have to continue to rely largely on contracts with their users. It is not entirely clear, however, whether a contract that appears momentarily on the screen prior to use is valid if the user has had no opportunity to negotiate the terms. Surely, information will not be shared with competitors unless some quid pro quo is offered or some eleemosynary motive is apparent. Giving away the fruits of intellectual labor without fair and equitable compensation is a policy not destined to survive the rigors of a marketplace economy.

At the other end of the spectrum of the debate over public and private information are the protesters who would like to control the distribution of personal information about themselves. As more computer networks come on line, more users are becoming aware that personal data are being gathered and correlated for someone else's purposes. The regulation of transaction-generated information, such as the records from telephone calls or credit card purchases, is a legal nightmare waiting to happen.

This issue caught the public interest through the controversy over caller I.D., or automated number identification, which allows holders of "800" numbers—or anyone subscribing to the service—to read a caller's number from a video terminal. This feature permits marketers to greet callers by their first names but, more important, to correlate their names and addresses with purchasing habits.

In fact, the telephone number is fast becoming at least as important an identifier as the social security card or the driver's license number (which is one and the same in many states). Transaction-generated information can be mixed and matched with census data, postal codes and such other publicly available information as automobile and boat registrations, birth registrations and death certificates.

The ease with which electronic impulses can be manipulated, modified and erased is hostile to a deliberate legal system.

This information, which has long been available to small marketers at a prohibitive cost from such large corporate information gatherers as Equifax Marketing Decision Systems, can provide precise profiles of potential buyers. But when Equifax joined forces with Lotus Development Corporation to offer an inexpensive product called Lotus Marketplace, a set of optical disks containing data on 80 million households and more than 120 million individuals, 30,000 people wrote in to have their names removed from the data base.

Yet that data base is typical of the type of information that is available when credit cards or any electronically readable media are used to make a purchase. K-Mart Corporation, Sears, Roebuck and Co. and J. L. Hudson Company collect point-of-sale data from credit card customers and either reward frequent buyers or appeal to their tastes and buying habits. One of the most aggressive of the new "relationship marketers" is Quaker Oats, which has a data base of 35 million households to whom it sends discount coupons and tracks their redemption. Citicorp has been experimenting with a data base of two million consenting customers who shop at supermarket chains across the country.

Clearly, the uproar over Lotus Marketplace, which caused it to be canceled, indicates that citizens are becoming apprehensive about the information about them that is being collected and correlated. Yet digital data are almost totally unregulated because they do not neatly fit into any of the legal boxes we have developed over the past 100 years. Traditionally the established laws governing communications apply specifically to mail, newspaper, cable television and radio broadcasting, in their separate legal pigeonholes. Signals in a digital environment do not differentiate among voice, video and data.

Already the lines between cable and broadcasting are becoming indistinct, as are the lines between what constitutes a common carrier (the telephone network) and a content provider (newspapers, journals and books). The common carriers, such as Bell operating companies, are petitioning to become information providers as a quid pro quo for installing optical fiber to the home that will facilitate the fully digital and networked environment of the future.

Ironically, the telephone companies are being besieged by demands to exercise control over the obscenity and pornography offered on the "900" paid-access calls, as anxious parents deplore salacious conversations as well as excessive charges on their telephone bills. But in late 1990, when Prodigy, an on-line service owned by IBM and Sears, admitted to controlling the content of messages posted on electronic bulletin boards, it met with just the opposite reaction from users.

Prodigy was accused of censorship for curtailing an on-line discussion critical of its rates and for discontinuing several controversial computer conferences involving sexual preferences. The public debate blossomed into a full-fledged airing of the nature of open discussion on electronic media.

Prodigy contended that it had the right to screen public messages posted on bulletin boards and conferences, on the basis that it was similar to the Walt Disney Productions cable channel, a family service. Many users disagreed. They likened the electronic forums in which they participated to the coffeehouses of Paris or a street corner or a private gathering in one of their homes.

Indeed, electronic bulletin boards (many operated by individuals who allow access only to their friends) have grown up in an atmosphere of open, uninhibited discussion. The WELL, for example, operates under the assumption that each person owns and is responsible for whatever he or she says.

Whether the law will recognize such individual responsibility and control in electronic media remains to be seen. Nor is it certain that the law will absolve the network provider from liabili-

ty for messages it allowed to be "published" or distributed. Indeed, there is considerable danger that the law will attempt to cover all electronic media under the same rubric without recognizing the vast diversity of networks—and diverse forms of communication within the same service—that are currently developing, some with unique cultures.

Law enforcement agents are stepping up the efforts to arrest computer hackers, a term that has come to mean unscrupulous youngsters who wreak havoc with computer systems. In February 1990 members of a hacker group called the Legion of Doom were arrested and charged with breaking into the computers of BellSouth. Three of the targets later pleaded guilty to stealing a BellSouth text file for its 911 emergency telephone system.

Then, in May 1990, a two-year Secret Service operation called Sundevil culminated in 27 simultaneous searches in which 40 computer systems were seized. One indictment for publishing the information was dropped because the defendant's lawyer convinced the authorities that the material was already published. Others are still awaiting indictment without the return of equipment that was seized.

Sundevil precipitated an outcry from computer professionals that constitutional rights were being trampled on, and the Electronic Frontier Foundation, devoted to protecting those rights, was established. The incident itself, however, is indicative of the confusion surrounding legal concepts that have survived the test of time in the noncomputer world but may not stand up to scrutiny in the electronic context.

Property has traditionally been something that can be transferred from place to place or person to person. Theft is defined as "depriving the owner of the use thereof." In an electronic environment, although a piece of software or a component of a data base may be valuable, the intruder who accesses it without authorization is not depriving the owners or authorized users of its use, unless the data are maliciously destroyed or distorted.

Some forms of miscreant behavior, such as introducing a message bearing a virus into a network, may not be destructive. Still, they may clog the computer's memory, denying authorized users access to their data. Any unauthorized entry alarms network managers because they fear some undesirable and deleterious consequence.

A "hacker" law recently enacted in the U.K. makes unauthorized entry punishable as a misdemeanor and entry with malicious intent a felony. In the U.S., several states have passed special legislation to expand their computer crime laws to cover the insertion of viruses and other rogue programs into software or network systems.

Proposed federal legislation would expand the Computer Fraud and Abuse Act of 1986 to cover "reckless disregard" for the consequences in addition to specific intent to cause damage or harm. There is also a move to enlarge the definition of venue. Such legislation would make it possible to try an alleged perpetrator in any state through which, from which or into which some part of the transmission is found to have occurred.

Cyberspace is a frontier where territorial rights are being established and electronic environments are being differentiated.

Another potential legal issue surrounds the ability of computers to alter and distort data and images. With computerized capability to cut and paste images, what you see may not be what actually took place. An incident that occurred in the weeks just before the election of November 6, 1990, in Massachusetts may be a harbinger of more widespread controversies. A popular Boston television journalist, Natalie Jacobson, interviewed the two contenders in the gubernatorial race. Both candidates, John Silber and William Weld, were filmed in their homes to let the viewers see the intimate sides of their characters and family lives.

During the interview, however, Silber berated the audience for denigrating those women who, like one of his daughters (as well as his wife), chose to dedicate their lives to the care of husband, home and children. The implication of his comments was that working mothers who left children in day care were selfish and uncaring.

The outburst so ruffled working women, a large voting bloc, that the Weld campaign incorporated this segment into a political advertisement. The image of Silber, however, was enlarged and slightly distorted, so that he appeared more menacing than in the original shot. In addition, taking the conversation out of context made his words sound more threatening. The ad was widely criticized, and the Silber campaign took immediate action to have it withdrawn.

The incident raises interesting political as well as legal issues about the ease with which voice, data and images can be downloaded and manipulated almost instantaneously for retransmission. Should a temporary restraining order have been available to prevent television stations from broadcasting the spot or would that have constituted prior restraint? Should Silber have a case against Weld for libel or slander? If so, what is the appropriate penalty, recompense or sanction?

On the other hand, should the television station have a right of action against the Weld campaign or other broadcasters for copyright infringement for carrying an excerpt from a copyrighted newsmagazine? Should the television correspondent have a right of action against Weld for distorting the image or changing its context? Was the copying and rebroadcast of the segment a "fair use" of her work product?

Still other relatively unexplored legal territory surrounds the way companies conduct business over networks. A recent California case, *Revlon* v. *Logisticon, Inc.*, was the computer-age equivalent of shutting off the phones for nonpayment. On October 16, 1990, Logisticon, a software firm, brought the operations of Revlon, the cosmetics firm, to a dead halt by remotely disabling the software that managed the distribution of products from warehouse to retail stores. Logisticon justified the curtailment of service because Revlon had refused to make the next scheduled payment under its contract.

Logisticon's action, which was characterized by a Revlon vice president as "commercial terrorism," resulted in a loss of three days of activity at Revlon's main distribution centers. Revlon raced to court, accusing Logisticon of extortion, breach of contract and trespass, among other complaints. Logisticon claimed a right to disable the software because Revlon had refused to honor the next payment.

The legal issues are myriad. Who "owned" the software installed within the Revlon business offices? Was the agreement a "purchase" of software or a "license" to use software? And does it make a difference? Did Logisticon act improperly by disengaging its software so precipitously, or was it acting within its legal rights in disabling the use of its proprietary product? Should it have disclosed to Revlon the existence of the remote capability to disable the software?

Even more important than the substance of the legal issues that will arise

from data networks is the question of what group will determine which laws or operating rules shall apply. Nowhere is this more clear than in the emergence of computer bulletin boards such as the WELL.

Without question, computer bulletin boards are an electronic hybrid, parts of which may be looked on either as public or private, depending on the desires of the participants. These are analogous to mail, conversations, journals, chitchat or meetings. Under normal circumstances, this electronic environment might be considered more like a street corner where one is entitled to make informal remarks to one's intimate friends.

But many bulletin boards are accessed by users intent on "publication" for the record—scientists pursuing common interests in a research project, for instance. The cooperative writing may therefore have substantial historical, political or scientific value as a publishable research paper or journal article or treatise or textbook.

A community is usually governed by its duly enacted laws, which represent the ethical values of the group. But what if the computer conference or electronic bulletin board crosses the borders of two or more states or nations? In that case, more than one legal system may apply with rules that differ within the separate legal dominions. Should the community's laws be those of the geographic or the electronic locus? If the latter, how should the laws be promulgated? Who should administer them? What sanctions should enforce them? What institutions are responsible for resolving disputes in the global information marketplace?

Cyberspace is a frontier where territorial rights are being established and electronic environments are being differentiated in much the way the Western frontier was pushed back by voyageurs, pioneers, miners and cattlemen. And the entrepreneurs are arriving with their new institutions and information technology, in much the same way as the pony express and railroads pioneered communications networks during the 19th century.

Lawmaking is a complicated process that takes place in a larger universe than the confines of legislatures and courts. Many laws are never written. Many statutory laws are never enforced. Legal systems develop from community standards and consensual observance as well as from litigation and legislative determination. So, too, will the common law of cyberspace evolve as users express their concerns and seek consensual solutions to common problems.

Civil Liberties in Cyberspace

When does hacking turn from an exercise of civil liberties into crime?

by Mitchell Kapor

On March 1, 1990, the U.S. Secret Service raided the offices of Steve Jackson, an entrepreneurial publisher in Austin, Tex. Carrying a search warrant, the authorities confiscated computer hardware and software, the drafts of his about-to-be-released book and many business records of his company, Steve Jackson Games. They also seized the electronic bulletin-board system used by the publisher to communicate with customers and writers, thereby seizing all the private electronic mail on the system.

The Secret Service held some of the equipment and material for months, refusing to discuss their reasons for the raid. The publisher was forced to reconstruct his book from old manuscripts, to delay filling orders for it and to lay off half his staff. When the warrant application was finally unsealed months later, it confirmed that the publisher was never suspected of any crime.

Steve Jackson's legal difficulties are symptomatic of a widespread problem. During the past several years, dozens of individuals have been the subject of similar searches and seizures. In any other context, this warrant might never have been issued. By many interpretations, it disregarded the First and Fourth Amendments to the U.S. Constitution, as well as several existing privacy laws. But the government proceeded as if civil liberties did not apply. In this case, the government was investigating a new kind of crime—computer crime.

The circumstances vary, but a disproportionate number of cases share a common thread: the serious misunderstanding of computer-based communication and its implications for civil liberties. We now face the task of adapting our legal institutions and societal expectations to the cultural phenomena that even now are springing up from communications technology.

Our society has made a commitment to openness and to free communication. But if our legal and social institutions fail to adapt to new technology, basic access to the global electronic media could be seen as a privilege, granted to those who play by the strictest rules, rather than as a right held by anyone who needs to communicate. To assure that these freedoms are not compromised, a group of computer experts, including myself, founded the Electronic Frontier Foundation (EFF) in 1990.

In many respects, it was odd that Steve Jackson Games got caught up in a computer crime investigation at all. The company publishes a popular, award-winning series of fantasy role-playing games, produced in the form of elaborate rule books. The raid took place only because law enforcement officials misunderstood the technologies—computer bulletin-board systems (BBSs) and on-line forums—and misread the cultural phenomena that those technologies engender.

Like a growing number of businesses, Steve Jackson Games operated an electronic bulletin board to facilitate

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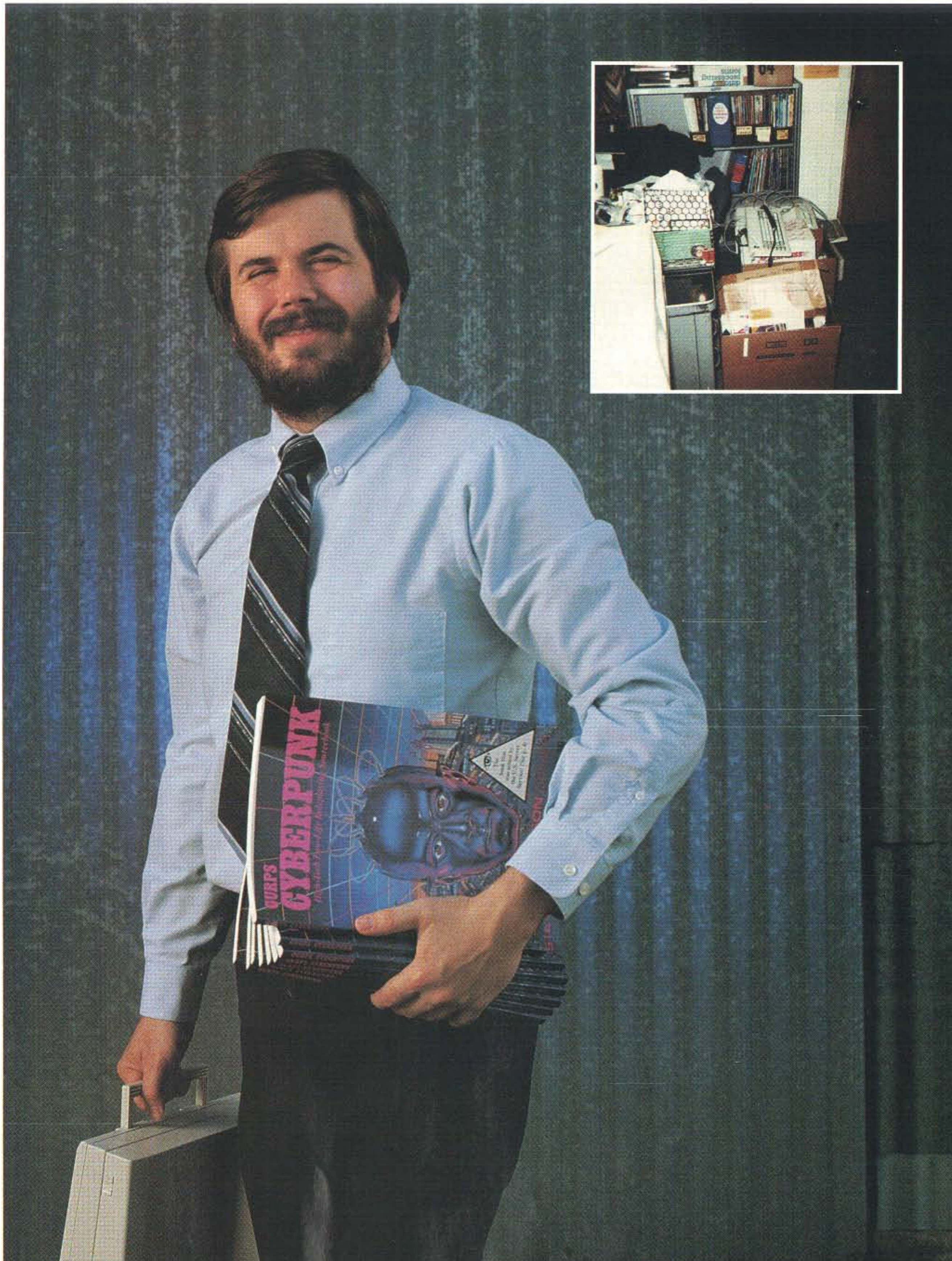

GAME PUBLISHER Steve Jackson maintains that his civil rights were violated when the Secret Service seized computers, business records and manuscripts. As a "receipt," Jackson says agents left a Polaroid of his boxed possessions (*inset*).

contact between players of its games and their authors. Users of this bulletin-board system dialed in via modem from their personal computers to swap strategy tips, learn about game upgrades, exchange electronic mail and discuss games and other topics.

Law enforcement officers apparently became suspicious when a Steve Jackson Games employee—on his own time and on a BBS he ran from his house—made an innocuous comment about a public domain protocol for transferring computer files called Kermit. In addition, officials claimed that at one time the employee had had on an electronic bulletin board a copy of *Phrack*, a widely disseminated electronic publication, that included information they believed to have been stolen from a BellSouth computer.

The law enforcement officials interpreted these facts as unusual enough to justify not only a search and seizure at the employee's residence but also the search of Steve Jackson Games and the seizure of enough equipment to disrupt the business seriously. Among the items confiscated were all the hard copies and electronically stored copies of the manuscript of a rule book for a role-playing game called GURPS Cyberpunk, in which inhabitants of so-called cyberspace invade corporate and government computer systems and steal sensitive data. Law enforcement agents regarded the book, in the words of one, as "a handbook for computer crime."

A basic knowledge of the kinds of computer intrusion that are technically possible would have enabled the agents to see that GURPS Cyberpunk was nothing more than a science fiction creation and that Kermit was simply a legal, frequently used computer program. Unfortunately, the agents assigned to investigate computer crime did not know what—if anything—was evidence of criminal activity. Therefore, they intruded on a small business without a reasonable basis for believing that a crime had been committed and conducted a search and seizure without looking for "particular" evidence, in violation of the Fourth Amendment of the Constitution.

Searches and seizures of such computer systems affect the rights of not only their owners and operators but also the users of those systems. Although most BBS users have never been in the same room with the actual computer that carries their postings, they legitimately expect their electronic mail to be private and their lawful associations to be protected.

The community of bulletin-board users and computer networkers may be small, but precedents must be understood in a greater context. As forums for debate and information exchange, computer-based bulletin boards and conferencing systems support some of the most vigorous exercise of the First Amendment freedoms of expression and association that this country has ever seen. Moreover, they are evolving rapidly into large-scale public information and communications utilities.

These utilities will probably converge into a digital national public network that will connect nearly all homes and businesses in the U.S. This network will serve as a main conduit for commerce, learning, education and entertainment in our society, distributing images and video signals as well as text and voice. Much of the content of this network will be private messages serving as "virtual" town halls, village greens and coffeehouses, where people post their ideas in public or semipublic forums.

If our legal and social institutions fail to adapt, access to electronic media could be a privilege, rather than a right.

Yet there is a common perception that a defense of electronic civil liberties is somehow opposed to legitimate concerns about the prevention of computer crime. The conflict arises, in part, because the popular hysteria about the technically sophisticated youths known as hackers has drowned out reasonable discussion.

Perhaps inspired by the popular movie *WarGames*, the general public began in the 1980s to perceive computer hackers as threats to the safety of this country's vital computer systems. But the image of hackers as malevolent is purchased at the price of ignoring the underlying reality—the typical teenage hacker is simply tempted by the prospect of exploring forbidden territory. Some are among our best and brightest technological talents: hackers of the 1960s and 1970s, for example, were so driven by their desire to master, understand and produce new hardware and software that they went on to start companies called Apple, Microsoft and Lotus.

How do we resolve this conflict? One solution is ensure that our scheme of civil and criminal laws provides sanctions in proportion to the offenses. A system in which an exploratory hacker receives more time in jail than a defendant convicted of assault violates our sense of justice. Our legal tradition historically has shown itself capable of making subtle and not-so-subtle distinctions among criminal offenses.

There are, of course, real threats to network and system security. The qualities that make the ideal network valuable—its popularity, its uniform commands, its ability to handle financial transactions and its international access—also make it vulnerable to a variety of abuses and accidents. It is certainly proper to hold hackers accountable for their offenses, but that accountability should never entail denying defendants the safeguards of the Bill of Rights, including the rights to free expression and association and to freedom from unreasonable searches and seizures.

We need statutory schemes that address the acts of true computer criminals (such as those who have created the growing problem of toll and credit-card fraud) while distinguishing between those criminals and hackers whose acts are most analogous to noncriminal trespass. And we need educated law enforcement officials who will be able to recognize and focus their efforts on the real threats.

The question then arises: How do we help our institutions, and perceptions, adapt? The first step is to articulate the kinds of values we want to see protected in the electronic society we are now shaping and to make an agenda for preserving the civil liberties that are central to that society. Then we can draw on the appropriate legal traditions that guide other media. The late Ithiel de Sola Pool argued in his influential book *Technologies of Freedom* that the medium of digital communications is heir to several traditions of control: the press, the common carrier and the broadcast media.

The freedom of the press to print and distribute is explicitly guaranteed by the First Amendment. This freedom is somewhat limited, particularly by laws governing obscenity and defamation, but the thrust of First Amendment law, especially in this century, prevents the government from imposing "prior restraint" on publications.

Like the railroad networks, the telephone networks follow common-carrier principles—they do not impose content restrictions on the "cargo" they carry. It would be unthinkable for the telephone company to monitor our calls routinely or cut off conversations because the subject matter was deemed offensive.

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cast media are grounded in the idea, arguably mistaken, that spectrum scarcity and the pervasiveness of the broadcast media warrant government allocation and control of access to broadcast frequencies (and some control of content). Access to this technology is open to any consumer who can purchase a radio or television set, but it is nowhere near as open for information producers.

Networks as they now operate contain elements of publishers, broadcasters, bookstores and telephones, but no one model fits. This hybrid demands new thinking or at least a new application of the old legal principles. As hybrids, computer networks also have some features that are unique among the communications media. For example, most conversations on bulletin boards, chat lines and conferencing systems are both public and private at once. The electronic communicator speaks to a group of individuals, only some of whom are known personally, in a discussion that may last for days or months.

But the dissemination is controlled, because the membership is limited to the handful of people who are in the virtual room, paying attention. Yet the result may also be "published"—an archival textual or voice record can be automatically preserved, and newcomers can read the backlog. Some people tend to equate on-line discussions with party (or party-line) conversations, whereas others compare them to newspapers and still others think of citizens band radio.

In this ambiguous context, free-speech controversies are likely to erupt. Last year an outcry went up against the popular Prodigy computer service, a joint venture of IBM and Sears, Roebuck and Co. The problem arose because Prodigy management regarded their service as essentially a "newspaper" or "magazine," for which a hierarchy of editorial control is appropriate. Some of Prodigy's customers, in contrast, regarded the service as more of a forum or meeting place.

When users of the system tried to protest Prodigy's policy, its editors responded by removing the discussion. When the protestors tried to use electronic mail as a substitute for electronic assembly, communicating through large mailing lists, Prodigy placed a limit on the number of messages each individual could send.

The Prodigy controversy illustrates an important principle that belongs on any civil liberties agenda for the future: freedom-of-speech issues will not disappear simply because a service provider has tried to impose a metaphor on its service. Subscribers sense, I believe, that freedom of speech on the networks is central for individuals to use electronic communications. Science fiction writer William Gibson once remarked that "the street finds its own uses for things." Network service providers will continue to discover that their customers will always find their own best uses for new media.

Freedom of speech on networks will be promoted by limiting content-based regulations and by promoting competition among providers of network services. The first is necessary because governments will be tempted to restrict the content of any information service they subsidize or regulate. The second is necessary because market competition is the most efficient means of ensuring that needs of network users will be met.

Network service providers will continue to discover that their customers will always find their own best uses for the new media.

The underlying network should essentially be a "carrier"—it should operate under a content-neutral regime in which access is available to any entity that can pay for it. The information and forum services would be "nodes" on this network. (Prodigy, like GEnie and CompuServe, currently maintains its own proprietary infrastructure, but a future version of Prodigy might share the same network with services like CompuServe.)

Each service would have its own unique character and charge its own rates. If a Prodigy-like entity correctly perceives a need for an electronic "newspaper" with strong editorial control, it will draw an audience. Other, less hierarchical services will share the network with that "newspaper" yet find their own market niches, varying by format and content.

The prerequisite for this kind of competition is a carrier capable of high-bandwidth traffic that is accessible to individuals in every community. Like common carriers, these network carriers should be seen as conduits for the distribution of electronic transmissions. They should not be allowed to change the content of a message or to discriminate among messages.

This kind of restriction will require shielding the carriers from legal liabilities for libel, obscenity and plagiarism. Today the ambiguous state of liability law has tempted some computer network carriers to reduce their risk by imposing content restrictions. This could be avoided by appropriate legislation. Our agenda requires both that the law shield carriers from liability based on content and that carriers not be allowed to discriminate.

All electronic "publishers" should be allowed equal access to networks. Ultimately, there could be hundreds of thousands of these information providers, as there are hundreds of thousands of print publishers today. As "nodes," they will be considered the conveners of the environments within which on-line assembly takes place.

None of the old definitions will suffice for this role. For example, to safeguard the potential of free and open inquiry, it is desirable to preserve each electronic publisher's control over the general flow and direction of material under his or her imprimatur—in effect, to give the "sysop," or system operator, the prerogatives and protections of a publisher.

But it is unreasonable to expect the sysop of a node to review every message or to hold the sysop to a publisher's standard of libel. Message traffic on many individually owned services is already too great for the sysop to review. We can only expect the trend to grow. Nor is it appropriate to compare nodes to broadcasters (an analogy likely to lead to licensing and content-based regulation). Unlike the broadcast media, nodes do not dominate the shared resource of a public community, and they are not a pervasive medium. To take part in a controversial discussion, a user must actively seek entry into the appropriate node, usually with a subscription and a password.

Anyone who objects to the content of a node can find hundreds of other systems where they might articulate their ideas more freely. The danger is if choice is somehow restricted: if all computer networks in the country are restrained from allowing discussion on particular subjects or if a publicly sponsored computer network limits discussion.

This is not to say that freedom-of-speech principles ought to protect all electronic communications. Exceptional cases, such as the BBS used primarily to traffic in stolen long-distance access codes or credit-card numbers, will always arise and pose problems of civil and criminal liability. We know that electronic freedom of speech, whether in public or private systems, cannot be

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absolute. In face-to-face conversation and printed matter today, it is commonly agreed that freedom of speech does not cover the communications inherent in criminal conspiracy, fraud, libel, incitement to lawless action and copyright infringement.

If there are to be limits on electronic freedom of speech, what precisely should those limits be? One answer to this question is the U.S. Supreme Court's 1969 decision in *Brandenburg* v. *Ohio.* The court ruled that no speech should be subject to prior restraint or criminal prosecution unless it is intended to incite and is likely to cause imminent lawless action.

In general, little speech or publication falls outside of the protections of the Brandenburg case, since most people are able to reflect before acting on a written or spoken suggestion. As in traditional media, any on-line messages should not be the basis of criminal prosecution unless the Brandenburg standard is met.

Other helpful precedents include cases relating to defamation and copyright infringement. Free speech does not mean one can damage a reputation or appropriate a copyrighted work without being called to account for it. And it probably does not mean that one can release a virus across the network in order to "send a message" to network subscribers. Although the distinction is trickier than it may first appear, the release of a destructive program, such as a virus, may be better analyzed as an act rather than as speech.

Following freedom of speech on our action agenda is freedom from unreasonable searches and seizures. The Steve Jackson case was one of many cases in which computer equipment and disks were seized and held—sometimes for months—often without a specific charge being filed. Even when only a few files were relevant to an investigation, entire computer systems, including printers, have been removed with their hundreds of files intact.

Such nonspecific seizures and searches of computer data allow "rummaging," in which officials browse through private files in search of incriminating evidence. In addition to violating the Fourth Amendment requirement that searches and seizures be "particular," these searches often run afoul of the Electronic Communications Privacy Act of 1986. This act prohibits the government from seizing or intercepting electronic communications without proper authorization. They also contravene the Privacy Protection Act of 1980, which prohibits the government from searching the offices of publishers for documents, including materials that are electronically stored.

We can expect that law enforcement agencies and civil libertarians will agree over time about the need to establish procedures for searches and seizures of "particular" computer data and hardware. Law enforcement officials will have to adhere to guidelines in the above statutes to achieve Fourth Amendment "particularity" while maximizing the efficiency of their searches. They also will have to be trained to make use of software tools that allow searches for particular files or particular information within files on even the most capacious hard disk or optical storage device.

Implementing a civil liberties agenda for computer networks will require participation by technically trained people.

Still another part of the solution will be law enforcement's abandonment of the myth of the clever criminal hobbyist. Once law enforcement no longer assumes worst-case behavior but looks instead for real evidence of criminal activity, its agents will learn to search and seize only what they need.

Developing and implementing a civil liberties agenda for computer networks will require increasing participation by technically trained people. Fortunately, there are signs that this is beginning to happen. The Computers, Freedom and Privacy Conference, held last spring in San Francisco, along with electronic conferences on the WELL (Whole Earth 'Lectronic Link) and other computer networks, have brought law enforcement officials, supposed hackers and interested members of the computer community together in a spirit of free and frank discussion. Such gatherings are beginning to work out the civil liberties guidelines for a networked society.

There is general agreement, for example, that a policy on electronic crime should offer protection for security and privacy on both individual and institutional systems. Defining a measure of damages and setting proportional punishment will require further good-faith deliberations by the community involved with electronic freedoms, including the Federal Bureau of Investigation, the Secret Service, the bar associations, technology groups, telephone companies and civil libertarians. It will be especially important to represent the damage caused by electronic crime accurately and to leave room for the valuable side of the hacker spirit: the interest in increasing legitimate understanding through exploration.

We hope to see a similar emerging consensus on security issues. Network systems should be designed not only to provide technical solutions to security problems but also to allow system operators to use them without infringing unduly on the rights of users. A security system that depends on wholesale monitoring of traffic, for example, would create more problems than it would solve.

Those parts of a system where damage would do the greatest harm—financial records, electronic mail, military data—should be protected. This involves installing more effective computer security measures, but it also means redefining the legal interpretations of copyright, intellectual property, computer crime and privacy so that system users are protected against individual criminals and abuses by large institutions. These policies should balance the need for civil liberties against the need for a secure, orderly, protected electronic society.

As we pursue that balance, of course, confrontations will continue to take place. In May of this year, Steve Jackson Games, with the support of the EFF, filed suit against the Secret Service, two individual Secret Service agents, an assistant U.S. attorney and others.

The EFF is not seeking confrontation for its own sake. One of the realities of our legal system is that one often has to fight for a legal or constitutional right in the courts in order to get it recognized outside the courts. One goal of the lawsuit is to establish clear grounds under which search and seizure of electronic media is "unreasonable" and unjust. Another is to establish the clear applicability of First Amendment principles to the new medium.

But the EFF's agenda extends far beyond litigation. Our larger agenda includes sponsoring a range of educational initiatives aimed at the public's general lack of familiarity with the technology and its potential. That is why there is an urgent need for technologically knowledgeable people to take part in the public debate over communications policy and to help spread their understanding of these issues. Fortunately, the very technology at stake—electronic conferencing—makes it easier than ever before to get involved in the debate.

Golden Screws

Micromechanical devices edge toward commercial uses

Fantastic Voyage, a 1966 film about a microscopic submarine that travels through the body, is a movie that the scientists and engineers who make microscopic machines and sensing devices love to hate. These micron-size wonders, which can make pinheads and strands of hair appear colossal, seemingly provide the makings for just such a tiny vessel.

But researchers who try to fathom the physical properties and forces of a world where specks of dust are floating boulders worry that comparisons with science fiction may lead to the overblown expectations that have caused disenchantment with other advanced technologies. "A lot of people were focused on miniature submarines," says Richard S. Muller, co-director of the University of California at Berkeley's Sensor & Actuator Center. "But this field is going to progress only by gradually adding new functions to integrated circuits."

The small community exploring micromechanics bears some of the blame. Micromachines captured the world's attention in 1988, when researchers from Berkeley demonstrated a motor that had a rotor diameter of only 60 microns. The team had concocted a machine with elements that had met the informal measure of the word "small" in the microscopic world: the diameter of the rotor was less than that of a human hair. Interest in micromechanical structures has continued to grow as both academic and industrial laboratories build an inventory of micron-size tools, machines and sensors that may one day equal a hardware store on a microchip.

Just as important as the stunning black-and-white scanning electron microscope images of tiny structures are the first attempts to understand what is needed to adapt micromechanical research to the large-scale manufacturing methods used for integrated circuits. "The implication has been that academic types were engaged in a gee-whiz show," says Stephen D. Senturia, a professor who is the senior researcher in micromechanics at the Massachusetts Institute of Technology. "Now there's beginning to be a cumulative body of science that can be communicated and used for manufacturing."

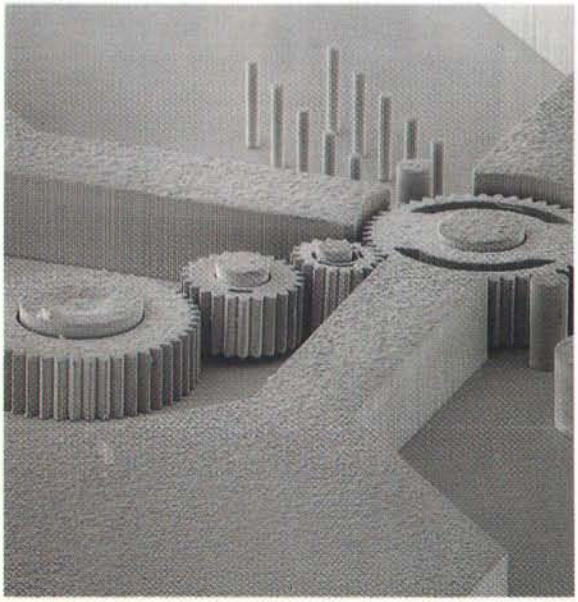
Senturia and others have begun to work on sifting and incorporating this knowledge into early versions of automated design systems that one day will make it possible to produce hundreds of chips on a silicon wafer, all of which integrate micromachines, sensors and electronic circuitry.

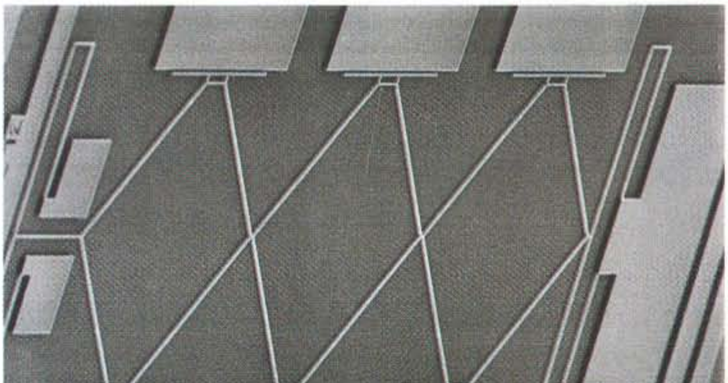
The task, however, is far more complex than etching simple electronic devices on a flat surface of silicon. Designers must model not just a flat array of circuits but a three-dimensional representation of the device's physical structure and properties. To help address this need, for example, a computer simulation has been designed to consider the varying rates at which chemicals reshape the faces of a silicon crystal to sculpt a device.

Although tiny motors that can barely move themselves made micromechanics famous, it is sensors that dominate the small initial marketplace. General Motors is probably the world's largest manufacturer of silicon microsensors, producing about 750,000 a month for detection of air pressure in engine intake manifolds. In medicine, some 10 million disposable blood-pressure sensors are produced every year.

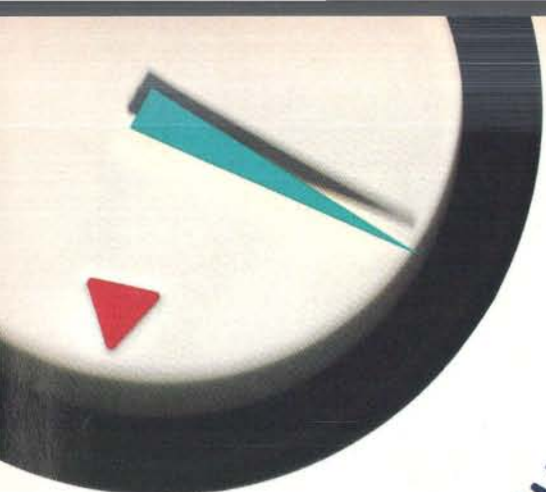
Established semiconductor firms are now taking a close look at a technique called surface micromachining. It employs the same photolithographic and etching steps that are used in fabricating integrated circuits. These processes allow sensors and the electronic circuits that control them to be manufactured together on the same chip. A critical difference between this method and conventional semiconductor processing lies in the chemical removal of a sacrificial layer of silicon dioxide below the surface. Removal of this layer releases a motor so that it can spin or suspends the diaphragm of a pressure sensor on a circular support structure.

One of the first products made by sur-





MICROMACHINES come in different sizes and shapes. Some of the 100-micron-thick gears on the University of Wisconsin's nickel motor are deeper than they are wide **(left).** *In contrast, the University of Tokyo's Institute of Industrial Science made a parallelogram actuator only four microns thick by chaining silicon polygons into a structure that resembles an electronic inchworm* **(above).**



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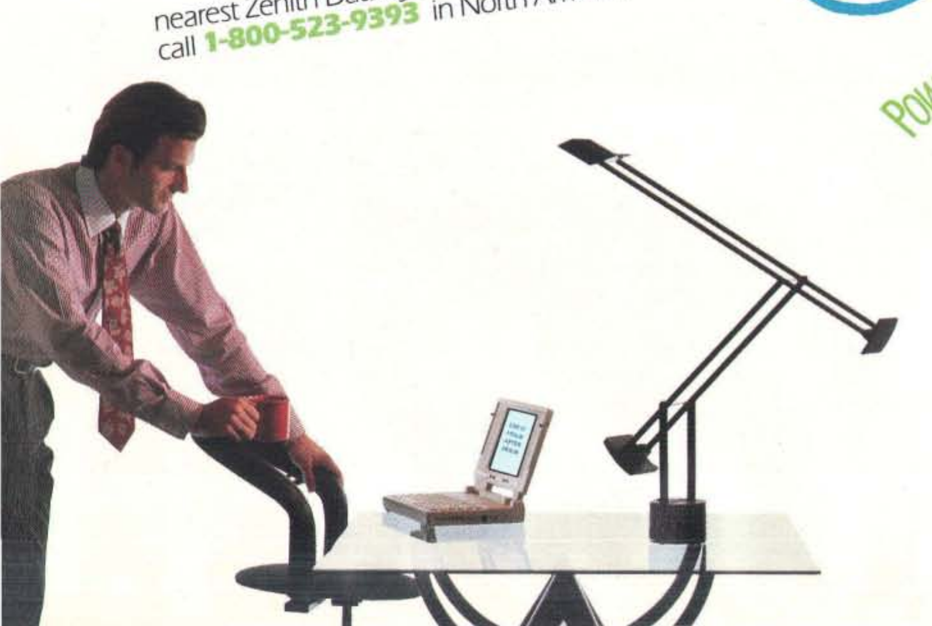


*Under normal rest/resume conditions. Battery life varies with application, CPU clock speed, memory configuration, peripheral options attached, hard disk access, and display settings.

face micromachining has just reached the market. In August, Analog Devices, a major supplier of signal-processing components, was scheduled to announce an accelerometer on a chip. The accelerometer translates the rapid movement of a silicon beam, suspended about a micron above the chip's surface, into an electrical signal, which is then processed by circuitry on the chip to activate an automotive air bag. The device will replace the bulky and expensive sensors—balls released into cups—that are currently used as triggers.

The Analog Devices product is an early example of the kind of "smart" sensors that engineers refer to as golden screws because they will make possible applications ranging from predicting machine failure to signature verification. "They may cost pennies, but without them a product will be so inferior that you can't sell it," says George A. Hazelrigg, the National Science Foundation's deputy director of electrical and communications systems.

Although sensors may become the eyes, ears and noses of integrated circuits, researchers still hope that motors, valves and other micromachines, also called actuators, will eventually become the stuff of truly small robots. So far solid state micromachines are still largely research curiosities, because an array of technical difficulties, from suppressing friction to connecting wires, keeps the tiny devices from finding practical application.

Creating a micromachine forceful enough to move an object is a fundamental challenge. "Motors barely have enough power to get over their own frictional loads," says Kaigham J. Gabriel, a researcher at AT&T Bell Laboratories.

Heated arguments arise over how to obtain more power from micromachines. Using conventional semiconductor processing produces a "pancake" machine of only a few microns in depth. To increase power and mechanical strength, a few researchers have begun to make replicas of larger machines by using metallic materials that can be fashioned into a higher-relief three-dimensional form.

At the recent Transducers '91, the Sixth International Conference on Solid-State Sensors and Actuators, Henry Guckel of the University of Wisconsin demonstrated a tiny electromagnetic motor made from nickel. It provided enough torque to drive seven tiny gears. The diameter of some of the gears spanned only a few dozen microns, yet each also had a thickness of 100 microns. Whereas most micromachines built so far are driven by electrostatics, Guckel's motor uses electromagnetic forces.

To make the motors, a synchrotron barrages uncovered sections of a thick polymer film with X rays. The exposed areas are then etched with a developing chemical to form a series of deep cavities. Nickel or another metal is electroplated into these cavities to make a part such as a gear. The film is etched away to release the structure.

The process has one disadvantage: it needs a costly synchrotron. Even so, Guckel believes it will be used to produce molds into which metal can be injected to produce millions of minuscule parts inexpensively.

Another group of researchers is betting that novel types of planar surfaces might still lead to machines that can produce enough force to move real loads. Gabriel of AT&T, who worked with a group from the Institute of In-

Learning How Bacteria Swim Could Set New Gears in Motion

Inside the black concrete Stanley Electric building on the edge of Tsukuba in Japan, engineers working on the next generation of automobile parts share space with some unusual benchmates. For the past five years, Stanley Electric has housed a team of biophysicists who have pursued a distant goal: using bacterial flagella as the basis for minuscule artificial molecular motors.

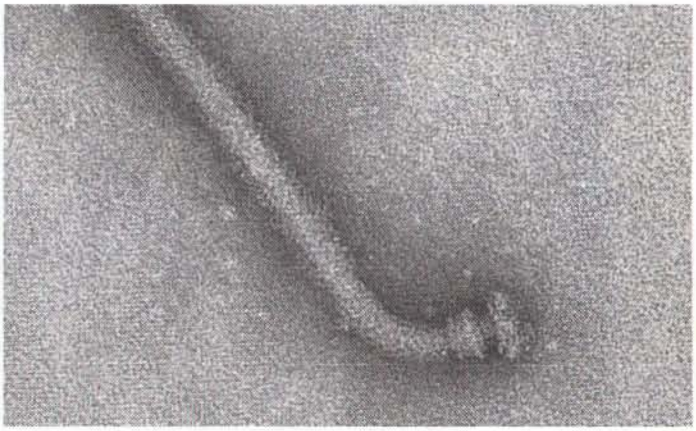
Such motors are far from ready for factory assembly. Yet even though the Hotani Molecular Dynamic Assembly Project draws to a close this September, team members say the progress they have made is impressive. "Our work has gone very well. We are beating other people, and they hate us," jokes Shin-Ichi Aizawa, one of the research team leaders.

The official objective of the Hotani project sounds deceptively simple: to discover how common bacteria, including *Salmonella* and *Escherichia coli,* swim. These bacteria are propelled by whiplike flagella, which are rotated by tiny molecular motors. As a result, "one of our dreams is the application of tiny motors," says project leader Hirokazu Hotani, who returns to Teikyo University as a professor in the department of biosciences this fall. Such molecular-scale motors could be used in countless ways—for instance, to propel machines the size of cells inside a patient's body to deliver therapeutic drugs.

In 1986 Hotani drew together 15 researchers to study the bacterial engines, complexes of proteins that measure only 30 nanometers in diameter. Yet like conventional electric motors, these rely on a rotor that revolves inside a stationary ring, or stator.

Hotani could pursue such a fundamental research project because he received a grant from Japan's Exploratory Research for Advanced Technology (ERATO) program, the country's most generous and, among Japanese researchers, most coveted funding schemes. He has received about $2 million a year (300 million yen) for the past five years with almost no strings attached. That freedom to travel, hire staff and buy equipment is almost unheard of in Japan.

The only catch to ERATO funding is that after five years, the project must end, and team members must find work in other organizations or university laboratories. That short life span also means that the projects typically rent space in a research facility rather than finding a permanent home. As a result, Hotani's group ended up sharing laboratory



SALMONELLA *FLAGELLUM has been isolated to help study the bacterium's motor. The terminal ring, which may be the rotor,*

dustrial Science at the University of Tokyo, constructed a simple actuator, four microns thick, in the shape of a parallelogram. It contracts like an accordian when an electrostatic charge is applied from capacitors that bracket two opposing sides.

Fashioning a chain of contractile parallelograms that move in sequence creates an electronic inchworm. It might exert enough force to switch fiber-optic waveguides between circuits.

Perhaps the most exciting prospect for micromechanics is as a prelude to nanomechanics. A small coterie of researchers believes that for micromechanics to succeed, it must keep pace with advances in electronics that are bringing down the size of circuit elements to far less than a micron.

Nanosensors already exist. The cone-shaped tips of scanning tunneling microscopes span only a few atoms. They can also perform real work. In fact, IBM reported in the July 12 issue of *Science* that a scanning tunneling microscope could be used to move single atoms of silicon. Despite the tips' smallness, the size of actuators that move the cones and accompanying support structures can make the microscope as big as a tennis ball.

Building nanoactuators will enhance the performance of nanosensors. And adding submicron actuators would increase by 1,000-fold the rate at which a microscope tip can vibrate and thus scan a surface. An array of tips and actuators might be used for storing data or for patterning semiconductor circuits. "You could put a terabit on a chip," asserts Noel C. MacDonald, director of the School of Electrical Engineering at Cornell University, where experimental nanoactuators have been built.

Commercial nanomachines are years away, however. It took MacDonald and two graduate students, Jason Yao and Susanne Arney, a year to figure out a way to cut a 150-nanometer hole in the side of a tiny beam to hook up a wire.

Despite the advances and the obvious commercial potential, some observers are concerned that micromechanics may end up on the list of technologies that the U.S. has ceded to foreign competitors. Hazelrigg of the National Science Foundation, one of the chief promoters of the technology, estimates that annual spending in the U.S. totals \$15 million on research, lagging behind the \$75 million spent in Germany and the \$30 million spent in Japan. (Japanese spending is expected to rise substantially next year as a roughly \$180-million government program stretching over 10 years gets fully funded.)

The commitment of U.S. industry is decidedly mixed. IBM is constructing a laboratory that will primarily be devoted to micromechanics at a facility in San Jose, Calif., which does extensive research on data storage. But AT&T, a pioneer in micromechanics, is refocusing research into other areas. Gabriel, the last of a team of six researchers who started work on micromechanics in 1986, is preparing to leave. "This is a field that has an enormous impact on AT&T, and the company dropped it," Hazelrigg laments.

Micromechanical systems will require persistent funding to benefit from the technology. A submarine coursing through the body may remain a filmmaker's fantasy. But studies are already under way on systems for cell fusion and nerve regeneration that may lead researchers on an equally fantastic voyage. *—Gary Stix*

benches with workers at Stanley Electric. Nevertheless, the time constraint does have advantages, insists Keiichi Namba, another research team leader. "Having a limited amount of time makes people concentrate," he says.

The scientists have made good use of their time. The intense scrutiny of bacterial flagella has revealed much about one of nature's smallest mechanical devices. The cell walls of *Salmonella* bacteria are home to about 20 flagellar motors; of these, only six or seven operate and have filaments attached. As the *Salmonella* search for nutrients in their fluid environment, these motors rotate a bundle of helical flagella at speeds of about 15,000 revolutions per minute.

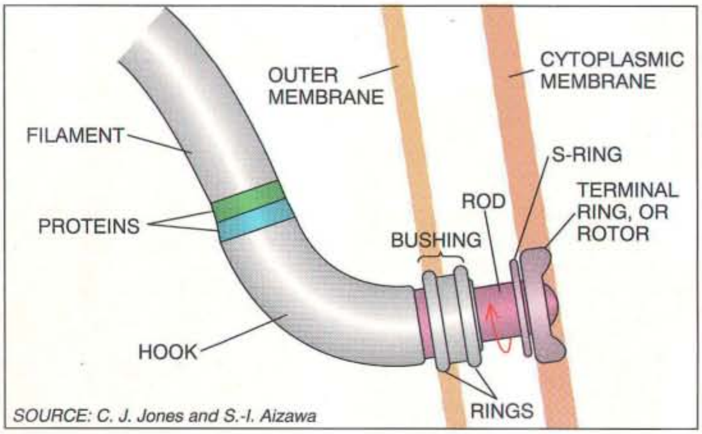
The Hotani project has focused on understanding the structure and mechanics of the system. For instance, Aizawa recently disproved a long-held idea that one of the structures on the motor, the S-ring, is a separate protein. Instead Aizawa's group has shown that the ring is part of a single, enormous folded protein, which makes up the base of the rotor. This discovery completes an important part of the puzzle of the flagellar motor structure, which consists of 10 kinds of proteins. Researchers are now turning to cloning the genes that create the proteins in the rotor structure and to understanding direct assembly, Aizawa says.

Elsewhere in the laboratory, Namba has developed a detailed computer model of a flagellar filament. The model required three years of careful measurements before Namba could visualize the intricate arrangement of flagellins, the stacked, barbell-shaped proteins that make up filaments.

Namba plans to continue gathering images in order to develop an even more finely detailed model, which he hopes will eventually show the arrangement of molecules in the flagellin. Understanding how those molecules interact will clarify the mechanics of how the filaments are constructed and how they operate—a necessary step on the way to making artificial molecular motors.

The final major step in piecing together the structure of the motor will be to identify its stator, which the rotator pushes against. Because the stators are embedded in the cytoplasmic membrane, they have been difficult to analyze.

People may be making artificial flagella in 10 to 20 years, Aizawa predicts, and then cheerfully concedes that he thinks most research will bear fruit in a decade or so. Namba, too, remains certain that work on the flagellar motor, which is an extremely energy efficient machine, will continue. "You never know," he adds, "but in 20 or 30 years, the basic knowledge of molecular machines and how to make them could produce some useful applications." *—Tom Koppel, Tokyo*



is believed to rotate with the rod, which transmits torque generated at the cytoplasmic membrane to the filament.

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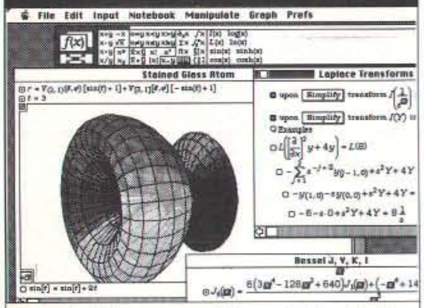

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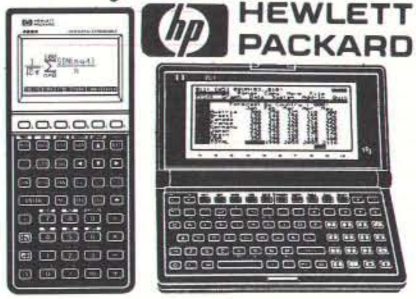

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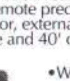

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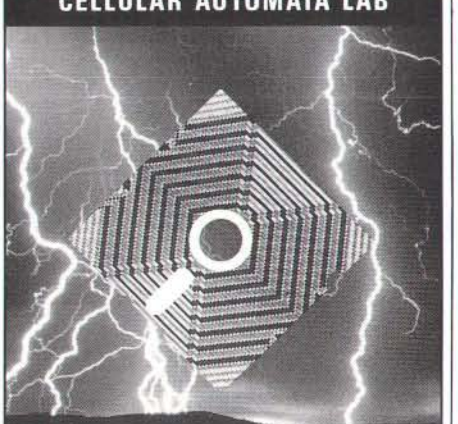

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True Blue

A zinc compound adds to the laser spectrum

Red semiconductor lasers serve well in reading data from optical disks and for a multitude of other applications. But consumer electronics manufacturers have never been content with the color: they pine for the other end of the spectrum. Because blue is the shortest wavelength of visible light, such a laser would permit compact discs to be loaded with more information or provide the basis for very high resolution color printers.

Until recently, researchers had been hard-pressed to coax semiconductors to emit even a little blue light. But at the recent 49th annual Device Research Conference, a team from the 3M Company reported they had created the shortest-wavelength diode laser yet—one that emits blue-green light. Michael A. Haase and his colleagues built the laser from the compound semiconductor material zinc selenide. "This is a real breakthrough," says Gregory E. Stillman of the University of Illinois.

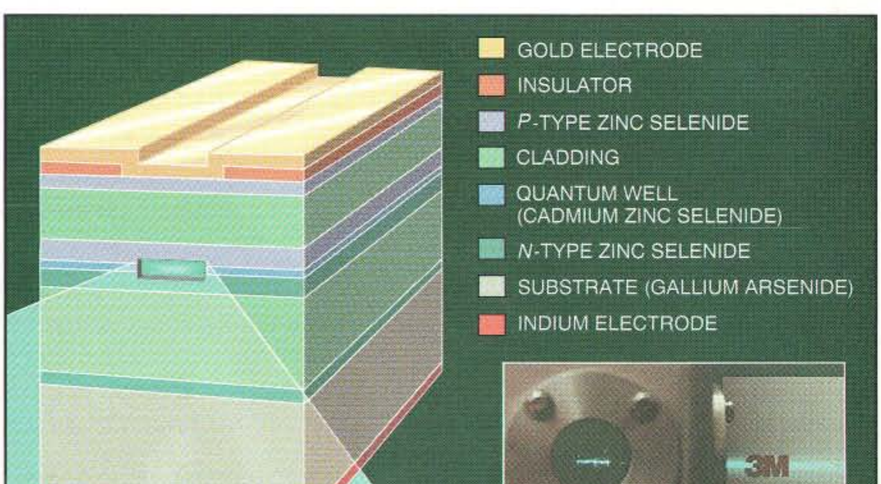
The 3M lasers produce light that has a wavelength of 490 nanometers when cooled to –9 degrees Fahrenheit. "Some people say that's a nice day in St. Paul," Haase quips. "True blue" is about 465 nanometers.

The construction blueprints for the devices are similar to those used for some of the most advanced solid state lasers: 3M built so-called quantum well lasers, in which electrons are pushed to higher energy levels by confining them in two dimensions. Such a quantum well amounts to a sliver of a compound semiconductor (in this case, cadmium zinc selenide) sandwiched between layers of a slightly different semiconductor material (zinc selenide).

Yet to make zinc selenide emit any light at all when pumped with electricity, the researchers had to solve a far more basic issue, namely, how to embed the proper charge carriers in the material. A light-emitting diode or a solid state laser must have a *p-n* junction, a place where positive-charge carriers (holes) recombine with incoming negative charges (electrons) and so emit light, or photons. The energy difference between the electrons and holes, called the band gap, determines the wavelength of the emitted light.

For almost 30 years, researchers have known that zinc selenide offered an ideal band gap for a blue laser. But adding enough positive-charge carriers to the material to create an effective *p-n* junction was a formidable task.

About a year ago the 3M investigators, along with former colleague Robert M. Park, now at the University of Florida at Gainesville, hit on a novel technique for embedding the necessary holes in zinc selenide. The group began by growing thin layers of zinc selenide on a gallium arsenide wafer in a molecular-beam epitaxy (MBE) machine. As the layers formed, the researchers exposed the wafer to nitrogen gas that was excited by radio waves. "The nitrogen is activated by the plasma in some unspecified way," Haase says. The nitrogen then embeds a sufficient concentration of holes into the material to enable it to produce light.



ZINC SELENIDE LASER, built by the 3M Company, emits blue-green light. It is made with thin layers of compound semiconductors.

At first, Park and the others simply built blue light-emitting diodes. Then Haase and Jun Qiu, James M. DePuydt and Hwa Cheng constructed a quantum well of zinc cadmium selenide and found they had a laser. "The very first one worked," Haase reports. "That's why we're so optimistic."

After meeting with 3M's patent attorney, Haase and his colleagues began writing technical papers. They paused only long enough to fabricate a second wafer—which also worked—to prove the first result had not been a fluke. Although those lasers operate at low temperatures, Haase is confident his team can build devices that will work at room temperature by adding more cadmium to the quantum well. He expects this laser will be "a little more green," say, lasing at 520 nanometers.

There is at least one major hurdle that the researchers must still clear. To produce light, they must pump about 20 volts into the zinc selenide lasers—a huge voltage for solid state lasers, which usually operate on two or three volts. Putting such enormous power into a device risks burning up the components. The power requirements have also forced the scientists to run their devices as pulsed rather than as continuous-wave lasers.

The reason the devices seem so power hungry, Haase says, lies with the nature of the electrical contact that must be put on top of the semiconductor layers. "The technology to make low-resistance contacts with [positive-charge-carrying] zinc selenide isn't here yet," he concedes. He is cautiously hopeful that his team can develop a lower-resistance contact. "It's a field of active research here. Very active," Haase emphasizes.

Meanwhile 3M is already looking for ways to put the devices to use. "We're teetering on the brink of the development stage," Haase says. "Right now, I've heard every conceivable possibility mentioned in the meetings I go to."

Elsewhere, other groups are trying to replicate the 3M results. A team of workers at Matsushita in Japan has successfully added positive-charge carriers to zinc selenide but has yet to report building devices. Other U.S. investigators are trying to customize their MBE machines to be able to excite nitrogen gas. "It's not trivial to put a radio-frequency plasma generator into an MBE," Stillman points out.

Even so, Stillman remains enthusiastic. "We know that there are still a lot of problems to be solved," he observes. "But just the fact they can show that the laser diode works is a real accomplishment."—*Elizabeth Corcoran*

Moles at Work

Local utilities may no longer say, "Dig we must"

The state of the art in technology for public works has not progressed much further than the venerable backhoe. The monotonous task of laying a new sewer still consists of excavating a ditch, laying pipe and filling the trench with dirt. Damage to the roadway, sidewalks, not to mention the commuter's day, can be serious.

A small group of contractors and their suppliers, however, are trying to make rush hour more bearable. In their specialty, called trenchless construction, they use high-pressure water jets or rotary cutting tools to carve out cavities large enough to accommodate a pipe or cable. "This technology will change the way we install utilities in urban areas over the next few decades," predicts Raymond L. Sterling, director of the underground space center at the University of Minnesota.

Perhaps the most sophisticated example of trenchless technology is microtunneling. These tunneling devices are miniature versions of the monster machines used by the Anglo-French team to dig below the English Channel. Bearing names such as Crunchingmole and Pirana, they sell for $500,000 to more than $1 million apiece.

Microtunneling machines were developed in Japan in the mid-1970s for use in congested urban areas. These boring machines, some of which have ferocious grins painted on their cylindrical exteriors, could have played bit parts in an old horror movie or been featured in the comics. "I can remember seeing Superman comics in the 1950s that had characters not so dissimilar from the machines we're using," quips Philip J. Coller, president of Iseki Poly-Tech, Inc., a U.S. affiliate of a Japanese company that makes the tunneling machines.

One of the first breakthroughs for microtunneling in the U.S. occurred in 1987. A group of homeowners in a swank Houston suburb resisted letting the city tear up their quiet streets and manicured lawns to install a new sewer system. Since then, microtunneling has been used for more than 20 projects.

Seven-foot-long microtunneling machines, also called moles, use rotary cutting heads that can slant up, down or sideways to carve eight- to 36-inch-diameter holes through soils ranging from clay to soft rock. They can also replace old pipes with new ones. The mole's cutting head turns and mixes up excavated material, which is pumped in a slurry to the surface. The ever present danger of tunnel collapse is minimized by pumping back the slurry, with sediment removed, to counterbalance losses in groundwater pressure. The cutting head is set to maintain a specific pressure on the earth through which the machine is burrowing. A jack in a vertical shaft behind the cutting head pushes pipe into the hole as the mole advances. A tunnel of up to 1,500 feet can be drilled before having to drop a new shaft.

Iseki is even trying to develop a "smart" mole. The company recently equipped one with a guidance control system based on "fuzzy" logic, a computer program that responds to vague concepts, such as "much" and "little." The fuzzy logic system compares the machine's present position with data from previous jobs to calculate how to maneuver to maintain a desired path.

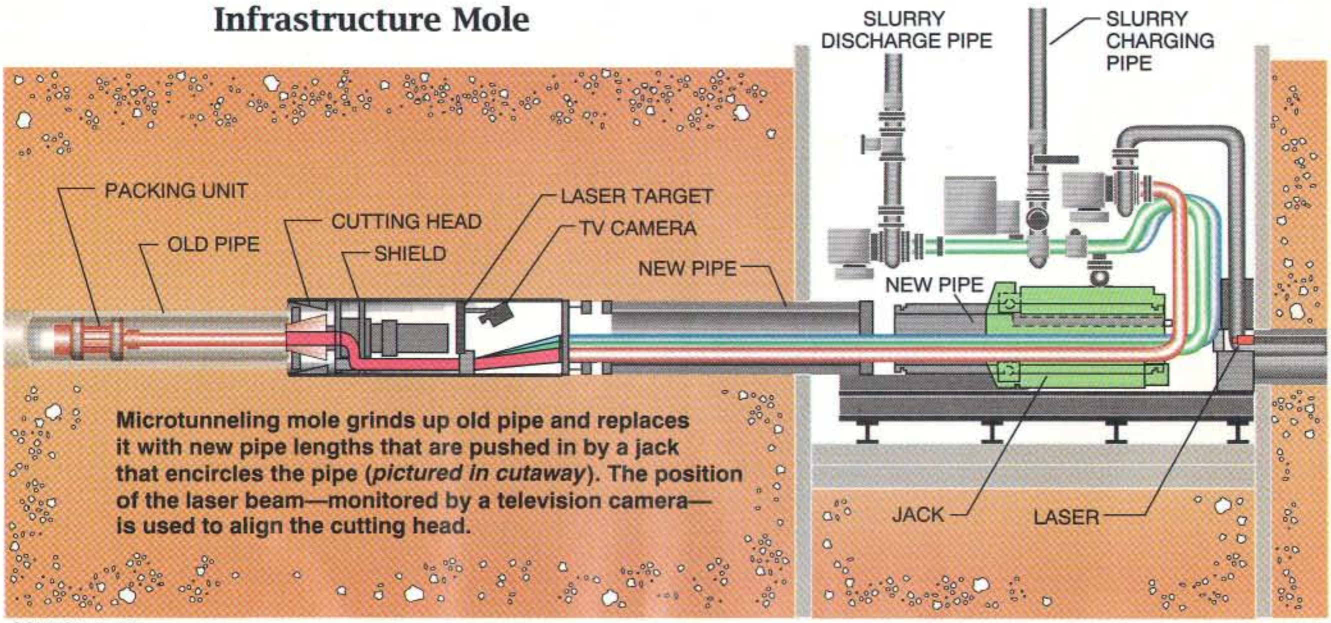
In some respects, microtunneling is harder than carving a hole big enough to drive a truck through because an operator seated at a control panel on the surface must direct the device remotely. So, as for larger projects, a laser aligns the cutting head to within an inch of where the beam is targeted.

Still, before microtunneling makes the backhoe a museum piece, costs must drop. A National Research Council study found that fees for microtunneling ranged up to almost five times the $50 a foot for open-trench excavation, although it may sometimes be cheaper.

Despite continuing cutbacks in municipal services, contractors who specialize in trenchless construction have been busy. D. Thomas Iseley, director of the trenchless excavation center at Louisiana Tech University, believes microtunneling will prove economical where deep sewers are required or where excavation may upset a fragile urban ecosystem. The technique was employed for part of a project in Milwaukee because it allowed pipe to be laid without having to drain groundwater, which could have unsettled the foundations of aging downtown buildings.

Microtunneling may eventually be used for more exotic applications—burying hazardous wastes, for example. Indeed, contractors who attend the annual "No Dig" conferences held by the International Society for Trenchless Technology believe the future is bright for their moles. —*Gary Stix*

Infrastructure Mole



Microtunneling mole grinds up old pipe and replaces it with new pipe lengths that are pushed in by a jack that encircles the pipe (*pictured in cutaway*). The position of the laser beam—monitored by a television camera—is used to align the cutting head.

SOURCE: Iseki

Industrial Immunology

Antibodies may catalyze commercial chemistry

No one has ever seen the molecule Mark A. Gallop wants to make because it exists for less than a millionth of a second. Gallop, who is coordinator of the bio-organic chemistry group at Affymax in Palo Alto, Calif., is trying to create a synthetic analogue of the active site of an enzyme at the exact instant that it binds to its target. The enzyme in question transforms a chemical precursor into a novel relative of isopenicillin. The researcher plans to expose immune system cells to those analogues. If all goes well, the antibodies that result will act on the penicillin precursor, enabling a simple manufacturing route to a new, hopefully more effective version of this common antibiotic.

Gallop is one of a group of investigators who are trying to find applications for antibodies in pharmaceutical and industrial chemistry. These researchers reason that the body spontaneously generates antibodies to bee venom, tetanus toxin and many millions of other non-self-compounds. So deliberately introducing a foreign substance, or antigen, should yield highly specific antibodies with whatever characteristics the material is designed to provoke.

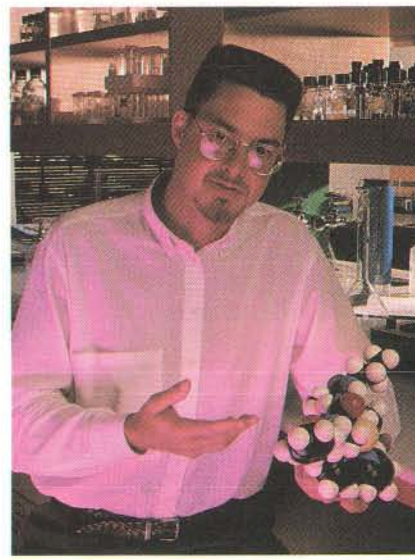
Antibodies made to recognize specific chemical bonds may function in the same manner as enzymes do to catalyze chemical reactions that do not occur in nature. Chemists have developed novel forms of drugs by complex and laborious organic chemistry, Gallop points out, "but they haven't been able to find enzymes to make them easily. We think catalytic antibodies may be able to perform the necessary reactions."

Affymax is hardly alone in its conviction that the immune system can become a font of new chemical catalysts. Several other small companies, including Igen in Rockville, Md., and Catalytic Antibodies, Inc., a start-up that grew out of research done at the University of California at San Francisco, are also developing catalytic antibodies. Major pharmaceutical firms, Rhone-Poulenc, among others, are funding research on them. Still others, such as Abbott Laboratories, are rumored to be setting up small, in-house study groups. The Japanese, who excel at enzyme manufacture, are said to have as many as 100 laboratories working in the area.

These companies believe catalytic antibodies will prove useful not only in the manufacture of drugs and other organic chemicals but also as therapeutics in their own right. The molecules, consisting of protein chains that cling together in Y shapes, might be able to treat cancer or rare diseases, dissolve blood clots or detoxify a body that has been exposed to nerve gas or drugs. But nearly all developers are keeping quiet about their specific interests to avoid tipping off competitors.

To make catalytic antibodies, researchers challenge immune cells with chemical analogues of the transition states that molecules pass through during a chemical reaction. The antibody produced in response is, in effect, trained to recognize that particular, briefly extant state. By binding to the site it has been educated to find, the antibody accelerates the chemical bonds' rate of change.

The result is often cleavage of part of



MARK GALLOP's model of an enzyme's active site may lead to a new way to make penicillin. Photo: Matthew Mulbry.

the bound molecule, so that the pieces can participate in other reactions. Once the separate reaction products are released, the antibody moves on to an intact molecule to repeat the process.

Binding specificity is crucial to achieving a useful catalytic antibody. Careful selection of an antigen is one step, "but it also depends on accidents," explains Richard A. Lerner, director of the Research Institute of Scripps Clinic in La Jolla, Calif., and a scientific adviser to Affymax. Any one antigen provokes production of as many as 40 to 50 antibodies, each of which sees different faces or regions of the molecule, Lerner explains. To enhance the effect, he has developed a technique called random-site mutagenesis that produces literally thousands of antibodies. "You look at

them all for the little nuances you don't know enough to program in. It's the difference between going to Las Vegas with one quarter or with 10,000 quarters," he says.

Selecting the best antibody from the large number of candidates remains one of the biggest obstacles to commercialization. Affymax, which has already developed a peptide screening technology, is working on several high-volume assays. In one, thousands of molecules tagged with fluorescent substances are attached to a testing plate. Only when a catalyst cleaves them is the glow revealed. The functioning antibody sticks to the plate and can then be identified.

One of the first commercial applications of catalytic antibodies is likely to be in the creation of "handed" pharmaceuticals, explains Kim D. Janda, a professor of molecular biology and chemistry at Scripps and an adviser to Catalytic Antibodies. Many drugs are produced with mirror opposites that are useless and so dilute potency. Some are even toxic. These could be captured by catalytic antibodies immobilized on glass beads inside reaction chambers.

Peter G. Schultz, a biochemist at the University of California at Berkeley and an Affymax founding scientist, suggests that catalytic antibodies may also find early applications in so-called prodrug delivery of cancer agents. Ordinary antibodies made to recognize tissues where tumors occur, in the lung or kidney, for instance, would carry a catalytic antibody to the site. The patient would then be given a dose of drug or toxin that would travel through the body in an inactive state until encountering the tumor. Catalytic antibodies bound there would recognize and cleave a bond in the drug to switch it on locally. Such targeted delivery could avoid the side effects of present cancer therapies, in which potent drugs circulate freely.

Before catalytic antibodies achieve widespread use, especially in high-volume industrial applications, production costs will have to be reduced. Until now, they have been cultured in mammalian cells, but recently inexpensive bacterial expression systems, such as *Escherichia coli*, have been shown to yield large quantities of antibody protein.

There are more than technical obstacles blocking the way to commercialization of catalytic antibodies. Litigation is already in progress about who owns what pieces of the technology. Researchers on all sides hint that the struggle just may catalyze development of more elegant science to cut through the tangle of patents and accusations. *—Deborah Erickson*

Trading Leisure Time for More Goods?

In the 1950s and early 1960s sociologists and economists began worrying about what Americans would do with a looming increase in leisure time. Labor-saving machines, such as robots in factories and automatic dishwashers in homes, promised to lighten Americans' labor loads dramatically. Departments of leisure studies sprang up at universities to examine the implications of coping with this unprecedented sociological challenge.

Yet the problem of too much leisure never materialized. Now economists are wrestling with more fundamental questions: How much leisure time do Americans have? Is leisure time shrinking or growing?

How people spend their time is of more than passing academic interest. Because time may be the scarcest resource in the economy, the way people spend it ultimately determines the relative prices of goods and services, the growth of national output and the distribution of income throughout society, suggests Frank P. Stafford, an economist at the University of Michigan.

People themselves are certainly preoccupied with how much time they work. Over the past decade, popular consensus has declared that Americans are indeed working more. But many economists believe that impression may have been shaped by the much-published results of a flawed poll.

That 1988 survey, conducted by Louis Harris and Associates, concluded that the workweek had increased from 40 hours in 1973 to 47 in 1988—about eight extra weeks of full-time work a year. But the 1973 pollsters had simply asked respondents how many hours they had spent on the job each week, whereas post-1980 polls tabulated the hours spent not only on the job but also on keeping house and going to school. As a result, total work hours were bound to rise, economists say.

Unfortunately, the data on work hours that economists cite are far less clear-cut than the popular impressions. Mainstream economists remain convinced that increased industrialization eases the burden of labor. In an article in the June issue of the *Journal of Economic Literature*, Stafford and a colleague, F. Thomas Juster, argue that work hours in several highly industrialized countries—namely, the U.S., Japan and Norway—have fallen since the 1960s.

According to their calculations, American men worked about 63.1 hours a week in 1965 but only 57.8 hours some 16 years later. American women similarly reduced their workweek from 60.9 to 54.4 hours. (Stafford and Juster include paid, market work and household work in their calculations.) But, Stafford hastens to add, not everyone is working less: "We've seen a time squeeze for subgroups of the population," he says. "Educated young women with kids just sleep less and don't watch much TV." On average, however, U.S. work hours have fallen, he maintains.

Other economists counter that the U.S. has fallen out of step with other industrialized nations and that work hours in America are indeed rising. In her book, the *Overworked American*, to be published this fall by Basic Books, Juliet B. Schor of Harvard University argues that over the past 20 years, fully employed people have increased the amount of time they work (at the office and at home) by as much as one extra month a year. They are working slightly longer days, Schor says, and most significantly, they are working more days of every year.

Fueling the clashes between these economists are differences in the data and in their interpretation. For instance,

Could it be that Americans are working more hours than they did several decades ago?

in 1975-76 and again in 1981-82, Stafford and Juster asked a sample of people to keep diaries in which they recorded their activities hour by hour. Keeping such diaries is widely acknowledged to be the most accurate technique for measuring the way people spend time. In interviews, respondents tend to report what they think they should be doing, Stafford points out. For instance, "people vastly overreport the time they spend taking care of their kids," he says.

Schor, nonetheless, takes issue with elements of the Michigan study. She points out that the surveys took place during recessions (when people might work less). So comparing those results with data gathered during a more prosperous turn in the business cycle in 1965 might cause work time to appear to fall and leisure to rise. Schor also contends that the surveys inadequately represented poor and minority workers. And, finally, she believes much of the increase in work time has occurred in the 10 years since the last Michigan data were collected.

Yet Schor's methods are also vulnerable to criticism. To construct a full data set, Schor had to calculate the number of hours people spend working both at home and at the job for several years. She derived her numbers from the Michigan data and from the "Current Population Survey," a monthly survey of the nation's labor force compiled by the Bureau of Labor Statistics. Many economists have criticized the reliability of the CPS numbers. Still Schor says that independent of the debate over the number of hours worked, people are now working more weeks a year.

Even if economists cannot agree on how many hours Americans are working, they do find some common ground: U.S. workers could, in principle, have experienced a greater increase in leisure time than they have. They would simply have had to trade in their gains in productivity for relaxation rather than for more goods and services.

Between 1965 and 1981, U.S. productivity, or work per hour, rose more than 25 percent; leisure, by Stafford's accounts, has grown at less than half that rate. "We've had the potential for increased leisure hours, but all of that has been channeled into increasing output," Schor says. "So the potential for increased leisure time provided by technological change has not been realized," she asserts. And people may not have much control over the trade off between leisure and goods, she adds. Their employers may, in essence, dictate the balance to them.

Even though Stafford believes workers have more free time than did their grandparents, he is less optimistic about the future. If the economy continues to stagnate, "we may end up working more across the board," whether we want to or not.

—*Elizabeth Corcoran and Paul Wallich*

Leaping into Lyapunov Space

While investigating digestion, Mario Markus of the Max Planck Institute for Nutrition discovered beauty in chaos. He and his collaborator Benno Hess have studied several mathematical models in an attempt to simulate how enzymes break down carbohydrates. By adjusting a pair of parameters, they found they could make the simulated enzymes behave in either an orderly or chaotic manner. To illustrate the chaos inherent in the model, Markus created a series of pictures that provided not only food for thought but also a feast for the eyes.

The images are based on a formula named after the Russian mathematician Aleksandr M. Lyapunov. The formula generates a single number for any dynamic system. Known as the Lyapunov exponent, the number indicates how chaotically the system is behaving. When the Lyapunov formula is applied to Markus's model, it produces an exponent for each pair of parameters. By representing each pair as a point on a computer screen and assigning colors to each point depending on the value of the exponent, Markus created what I call Lyapunov space. In this virtually unexplored territory, order inhabits colored shapes, and chaos lurks in black regions.

Not long after his work appeared in academic journals, Markus rushed several pictures to an art gallery for exhibition. He can hardly be blamed for doing so. The pictures could just as easily have been made by an apprentice to Salvador Dali.

The model developed by Markus is based on a variation of the so-called logistic formula, the simplest-known formula that describes a chaotic dynamic system. The formula contains a variable, x, whose value is always somewhere between 0 and 1. It also involves a system parameter, r. The formula can be written:

$$x \leftarrow rx(1 - x)$$

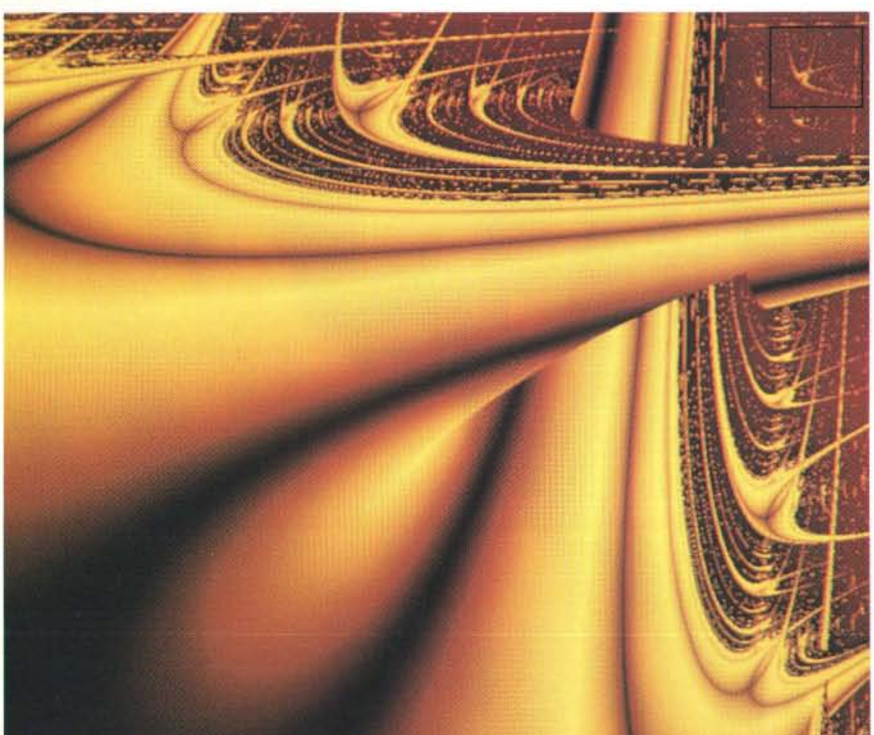
The arrow indicates that once r, x, and $1 - x$ have all been multiplied together, the resulting number becomes the new value for x, that is, it replaces the old value. The process can be repeated so that the formula continually spews out new values for x.

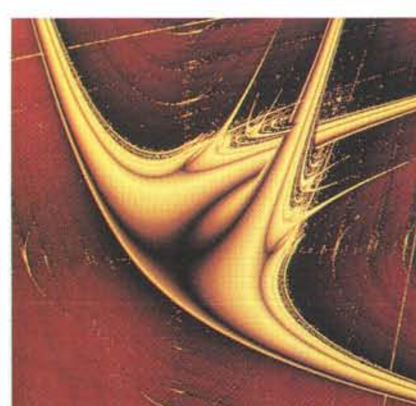
The resulting sequence holds great fascination for dynamicists, but what does it all mean? The logistic equation gets its name from the logistics of animal populations. In the equation, x represents the number of animals in an isolated region divided by the maximum number that the region could ever be expected to support. The amount of food available is therefore proportional to $1 - x$. In other words, as the number of animals (x) approaches the maximum (1), the food supply ($1 - x$) dwindles to nothing (0). The parameter r expresses the proportionality. It may be thought of as the fecundity of the population. The higher the value of r, the more quickly the population will rebound from any disaster. Strangely enough, higher values are precisely the ones that lead most quickly to chaotic populations.

Although the equation is too simple to represent real animal populations, it can serve as a rough approximation to population dynamics.

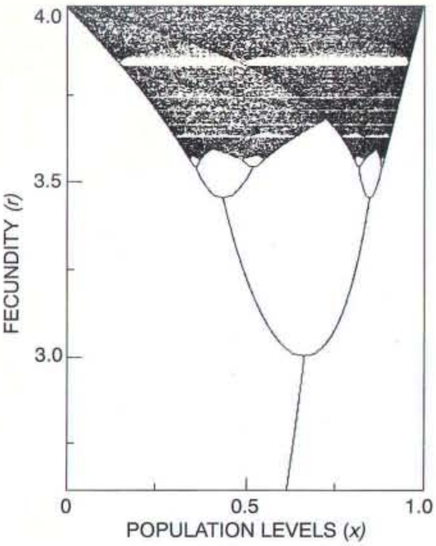
If the parameter r is less than 2, the sequence of numbers produced quickly homes in on a single value. It makes no difference what number the formula uses for x initially. The population always converges to a stable value. In the jargon of chaos theory, a system whose dynamics stabilize at a single value is said to have a one-point attractor.

If the parameter r is greater than 2 but less than about 2.45, the logistic formula generates numbers that even-

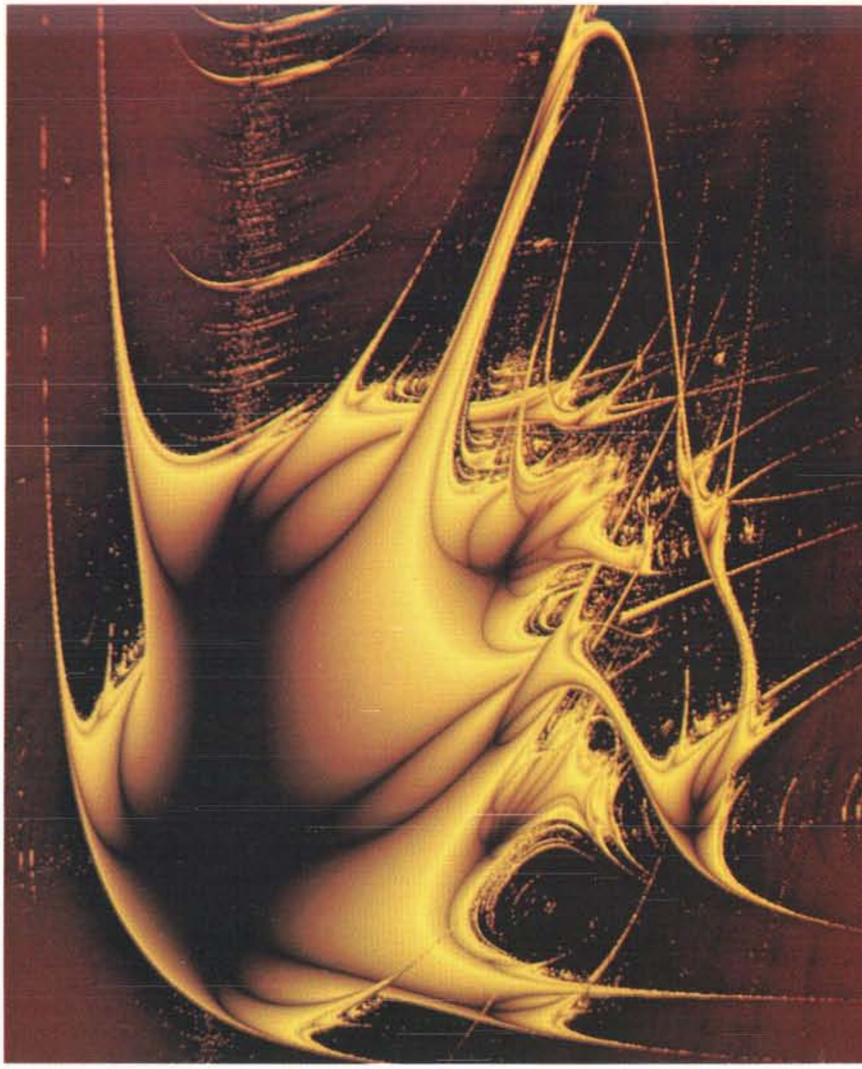




Lyapunov space* (left) *and a detail* (right) *showing the "swallow"



Population levels,* x*, can fluctuate over a wider range of values as the fecundity factor,* r*, increases.



A Lyapunov "jellyfish"

tually alternate between two values. The system then converges on a two-point attractor. In some sense, when fecundity is high, the population pays a price: its size fluctuates over time.

If the fecundity factor is cranked up to values greater than 2.45, the logistic formula produces numbers that converge on a four-point attractor. Still higher values of r lead very quickly to eight-point attractors, then 16-point ones and so on. But if the value of r is greater than 3.57 (or, to be more precise, 3.56994571869), chaos reigns.

At that level of fecundity, the formula seems to generate values at random, though, to be sure, the formula is deterministic. The reason for this strange behavior lies in the attractor. It happens to be a one-dimensional fractal. Like all fractals, it is self-similar: when any small piece of it is magnified, the enlarged region looks very much like the whole.

The fate of the hypothetical populations is clearly portrayed in the graph above. The diagram is produced by plotting r against the values to which the logistic formula converges. The result is a kind of tree. One-point attractors make up the trunk; two-point attractors, the first pair of branches. At an r value of 3.57, the onset of chaos can be seen clearly: the branches suddenly proliferate.

Chaos can be characterized using the Lyapunov formula. For each dynamic system, the formula produces a single number, the Lyapunov exponent. If the number is less than 0, the system is stable. If the number is greater than 0, the system is capable of chaotic behavior.

The Lyapunov formula is complicated, but it can be translated into a series of simple steps. In the case of the logistic system, we start with one particular value of r. The logistic formula is iterated, say, 600 times, so that the numbers converge to whatever attractor is present in the system. After the numbers settle down, it is safe to compute the Lyapunov exponent. The following recipe outlines the computation:

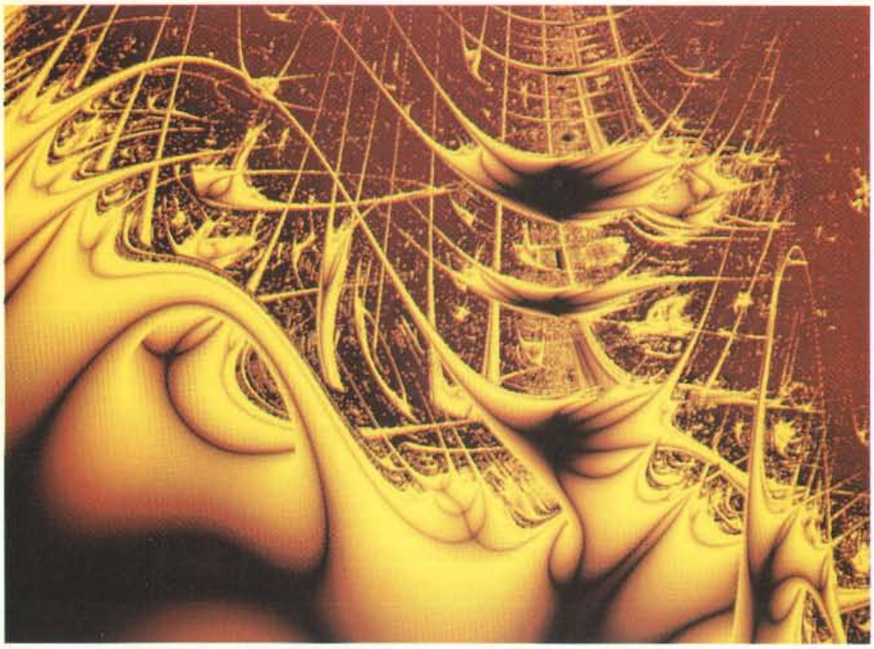
$\mathit{total} \leftarrow 0$
for $n \leftarrow 1$ to 4,000
  $x \leftarrow rx(1 - x)$
  $\mathit{total} \leftarrow \mathit{total} + ((\log |r - 2rx|) / \log 2)$
$\mathit{lyap} \leftarrow \mathit{total} / 4{,}000$

The algorithm first sets $\mathit{total} = 0$ and then iterates the logistic formula 4,000 times. On each iteration it computes a new value for *total* by adding the old value of *total* to the logarithm of $|r - 2rx|$ divided by the logarithm of 2. (The vertical bars indicate the absolute value of $r - 2rx$.) The quantity $|r - 2rx|$ represents the rate at which the magnitude of successive values is growing or shrinking. When it has added up all 4,000 logarithms, the algorithm divides the sum by 4,000. The result, which has been assigned to the variable *lyap* above, is something like an average logarithm of change. The result closely approximates the Lyapunov exponent.

Readers who demand precision can more accurately estimate the Lyapunov exponent by increasing the number of iterations and, at the end of the procedure, by dividing the sum of logarithms by the number of iterations.

I encourage readers to use the algorithm above to calculate the Lyapunov exponent for r equal to 2. Then compare the result with that obtained when r equals 3. The first number should be negative, indicating a stable system, and the second number should be positive, a warning of chaos.

The pictures accompanying this article are all based on the logistic equation. Markus merely adds one twist of his own. To produce his pictures, Mar-



Zircon Zity

kus used periodic forcing. This means that r systematically changes its value, alternating between two fixed numbers, a and b. In other words, the logistic equation is iterated with r values of a, then b, a, b, a, b and so on. The resulting system may or may not develop chaotic behavior. The issue can be settled only by calculating the Lyapunov exponent.

For that reason, Markus plotted the value of the exponent for each possible combination of a and b values. A two-dimensional image in Lyapunov space emerges when the points (a, b) are colored in some consistent fashion. Markus assigned black to all points (a, b) that produce a non-negative value for the Lyapunov exponent. Chaos is black. Shades of a single color, such as yellow, appear everywhere else in Lyapunov space. From a Lyapunov exponent of zero down to minus infinity, the shade ranges continuously from light to dark. At zero, there is an abrupt discontinuity as the color suddenly turns from bright yellow to black.

The resulting images are maps of chaos in the forced logistic system. In particular, the map on page 178 depicts the straightforward system just described. The parameter r alternates in completely regular fashion between a and b.

The crossing point of two or more spikes in any of the accompanying images reveals the coexistence of periodic attractors. This means that, at a point (a, b) where such a crossing occurs, the corresponding dynamic system in which r alternates between a and b will have two attractors. Which attractor operates depends, strangely enough, on the initial value that one chooses for x before iteration.

If the Lyapunov exponent is plotted for a succession of initial x values, it may take on a specific value, say, 0.015 for a number of these initial values. Then the exponent may suddenly switch to another value, 0.142, to which it may stick for several more successive initial x values before reverting to the first value. The switching back and forth can become quite frequent.

Lyapunov space often contains darkish bands that run along the spikes. These represent superstable regions in which the underlying forced logistic systems exhibit the most regular behavior.

The Lyapunov space generated by alternating a and b values contains a tiny fleck that resembles a swallow. The fleck is enlarged in the illustration on page 178. There, just off the swallow's tail, lies another little fleck. Readers are free to guess just what it might turn out to be when it is similarly enlarged.

The appearance of self-similarity in the figure should not surprise students of chaos. Structures that exhibit self-similarity are more often than not produced by chaotic processes.

The methods used to create the mother swallow and its offspring can be varied slightly to generate a host of different creatures. The images on these pages differ only in the a and b value sequences that were used. For example, a jellyfish—the yellow tentacled blob shown on the preceding page—is spawned from a sequence that begins b, b, a, b, a and that repeats over and over again.

The scene above resembles the cover of a science fiction magazine from the 1950s. I call it Zircon Zity because it is obviously the futuristic metropolis of the Zirconites (whoever they are). The underlying sequence of the zity is *bbbbbbaaaaaa*. By repeating this sequence while calculating the Lyapunov exponent, a computer can build the zity with all its delicate bridges, golden spaceships and interplanetary walkways.

What does all this have to do with enzymes, carbohydrates and nutrition? At best, a small region in some Lyapunov map might actually describe the dynamics of enzymes breaking down carbohydrates. But perhaps more to the point, Markus's work makes it possible to visualize the dynamics of periodic forcing. One might say he has made chaos easier to digest.

The Lyapunov Program

For those readers who wish to explore Lyapunov space, I can give a few hints about how they might create the appropriate program. The heart of the program should be a double loop that runs through values of a and b. To compute the Lyapunov exponent for each combination of a and b, the program should include a routine based on the algorithm given on page 179. The routine should allow various sequences of a's and b's to be stored in an array. The routine could enable the user to specify the sequence by filling the array with 0's (representing a) and 1's (representing b).

With each iteration of the Lyapunov loop, a counter called *index* may be used to step through the array. Each time the inner loop produces a new value for *index*, it will look up the current value of either a or b, depending on whether it finds a 0 or a 1 in the array at the value of *index*. Finally, the program should include a table of logarithms to help speed the computations. Indeed, it may take hours for a personal computer to generate a single image in Lyapunov space.

FURTHER READING

CHAOS IN MAPS WITH CONTINUOUS AND DISCONTINUOUS MAXIMA. Mario Markus in *Computers in Physics*, pages 481–493; September/October 1990.

THE MAGIC MACHINE: A HANDBOOK OF COMPUTER SECRECY. A. K. Dewdney. W. H. Freeman and Company, 1990.

BOOK REVIEWS by Philip Morrison

Tailpipes and Climate

PALEOCLIMATOLOGY, by Thomas J. Crowley and Gerald R. North. Oxford University Press, 1991 ($59.95). **CLIMATE CHANGE: THE IPCC SCIENTIFIC ASSESSMENT,** edited by J. T. Houghton, G. J. Jenkins and J. J. Ephraums. Published for the Intergovernmental Panel on Climate Change by Cambridge University Press, 1990 ($75; paperbound, $34.50).

Life has been nurtured for close to four gigayears in the airy greenhouse of the planet. Both these books examine the nature and course of that dynamic shelter. The Oxford volume is a readable and instructive monograph, technically temperate enough for serious readers in the sciences. Its authors, who provide an overview of geologic time, are two productive contributors to climate research, at work at Texas A&M. Cambridge offers a weighty study organized by the World Meteorological Organization and the United Nations Environment Program that documents human tampering with the global thermostat; its concerns look ahead a century, but back only to the last glaciations.

The IPCC expects among its readers the policymakers of the world, or at least their numerate advisers. The book has a dozen pointed chapters on models and methods, each by a small group of leading specialists, backed by a couple of dozen international contributors who took part both in meetings and in writing. The entire report was then reviewed by some 200 scientific peers in 30 countries, all of whom are acknowledged by name. All comments were considered. Although "there may be persons...who still have points of disagreement," the air of consensus is strong. The intent, however, is not so much that of explanation as it is of candid trial witness, intent on meeting objections fairly rather than clarifying the nature of the case. This review will seek to take the other road, using as a source both volumes, neither of them elementary.

We live in the greenhouse; we always have. The vital sunbeams come down through the air, a layer that consists mainly of the sunlight-transparent twinned atoms, O_2 and N_2. A distant astronomer—or one of our own satellites—sees this sky-blue and cloud-white planet by the third of the sunlight that the earth sends back. The land and the sea are intrinsically aglow as well; they radiate heat deep in the infrared.

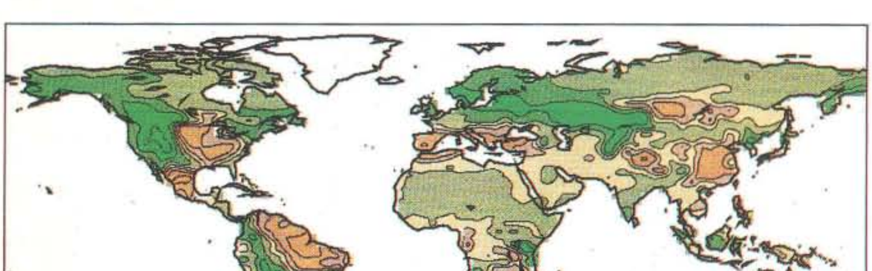
Yet a distant infrared observer could hardly make out the earth's surface; powerful absorbing layers of trace amounts of more complex molecules in the air intervene. Most of these molecules are made of three or four common atoms. The molecules include water vapor, carbon dioxide and methane, as well as rarer polyatomic traces of life and chemical engineering. What an observer would see in infrared is the surface of the world of weather, the radiating clouds and the layer of clear air at the base of the stratosphere seven miles up.

It is at altitude that the inevitable radiative energy balance between earth loss and solar input is therefore struck: at the temperature of a cold January day in Chicago. Down on the ground floor, the global average temperature is that of an April afternoon in New England. That difference, from overcoat, mittens and earmuffs to a light topcoat, is the greenhouse effect. Mainly it is the work of water vapor; perhaps a quarter of the effect comes from CO_2. Methane also contributes. Such molecules are tuned to achieve radiative potency; they are resonant though scarce. Water vapor is present at less than one in 1,000 among air molecules; carbon dioxide, staple food of green plants, is even scarcer. It is the very scarcity that sets a climatic trigger.

For each human, about a ton and a half of carbon as CO_2 enters the air annually. Fossil-fuel combustion is the main source. The replacement of overgrown forest floor by open farm fields also contributes significantly. The well-off puff CO_2 from myriad tailpipes; the numerous poor exude it from the coal briquettes they burn for warmth; we all live by plenty of fuel-fired nitrogen fertilizer.

For the five centuries before Elizabeth I, CO_2 was an unchanging ingredient of the atmosphere. We know because the polar ice caps remember. They store the accumulated snows of yesteryear foot by foot, along with the air entrapped as each succeeding year's snow crystals froze to bubbly ice. Near the surface we find datable, constant medieval air, its entire CO_2 content no more than what we now add within a century. Industrial humanity has suddenly spiked the atmosphere with CO_2. The content grows every year, as workers at the laboratory have demonstrated for a generation on the lofty summit of Mauna Loa. The possibility that this swift change is some natural fluctuation "can be dismissed" by simple and compelling arguments.

At frozen Vostok, the Soviet station at the Antarctic "pole of cold," they have extracted ice cores by the mile.



CHANGES IN SOIL MOISTURE caused by doubling levels of atmospheric CO_2 are simulated by a high-resolution computer model. Dark green indicates the greatest increase in moisture; dark tan, the smallest increase. (*From* Climate Change.)

Dating is not easy but well confirmed. A mile down, at the warm interglacial temperature maximum 120,000 years ago, we find a peak amount of CO_2 in the air, comparable with, though lower than, today's spike. The old peak appeared suddenly, considering that it was a purely geologic event. It came in a hundred centuries, to leave again more slowly as the glaciers grew. With time, the trapped air yields less and less CO_2, until at last the gas starts to rise again, 1,000 feet down in the ice and 20,000 years back in time. The curve of past local temperature of the polar snows followed—or maybe preceded—the gas.

The world warmed steadily for 10 millennia, the ice sheets receding, to welcome a new and sapient species. Under human forcing, CO_2 has gone up half again as high as either interglacial peak, and 100 times faster. The question is plain: What change in climate will the newly CO_2-enhanced greenhouse bring to the 21st century? The global modelers, skilled in complexities, can reply but can hardly estimate the errors of what they have had to leave out, usually ocean circulation and cloud microphysics. Among 20 different models in many countries, all concur on a warmer and wetter world, over a range that averages near five Fahrenheit degrees warmer, mainly in high-latitude winters, and a few inches a year rainier, mainly in already rainy tropics. More water vapor has enhanced the enhancement. That change would lead to a world climate without precedent, seas and air warmer but poles ice capped; the present thick caps cannot melt so fast. Sea level will rise by a foot or even by two.

A strict control on future fuel use would ameliorate the effects of such a business-as-usual scenario, but not fast enough to eliminate them. Reforestation propagated fast enough to trap the gas is an enormous task, equivalent to planting another Amazon basin in the next two generations.

The case is a little pat. The best global models are consistent, yet they are seriously incomplete. The experts believe, for instance, that the recent ice ages did not come and go by greenhouse changes but by changes in the seasonal amounts of solar input that come from known small variations in the earth's orbit and inclination. Those rhythmic perturbations are the result of lunar and planetary attraction, a real instance of astrology, gravity based. The evidence for the effect is very strong. All models of the past use changing solar input, at least implicitly; CO_2 fluctuations amplify the entire effect.

We do not even know whence came the natural CO_2 to feed those old bursts of gas. It was not from melting ice nor from the new glacier-edge wetlands. By far, most mobile carbon now lies in the cold depths of the sea. Was the new gas set free by some complex change in the cycle of plankton, or in sea-surface chemistry, or in gyres of deep-water circulation? Perhaps by volcanism? We simply don't know. In this system, where cause and effect are more web than chain, even the past is hard to predict.

The puzzle of the day is that the current account in which we deposit our CO_2 does not balance either. We know the gas is set free mainly in the continental north; it ought to be taken up mainly in the oceanic south. But it isn't. There is an unknown CO_2 sink on land, one that is large enough to take up a third or more of the man-made gas. Will that concealed removal continue, saturate or perhaps increase during the century to come? Will greenhouse gases accumulate as we reckon from the sources or somehow sink obscurely away?

One test seems to be close at hand: What changes in climate do we find so far from the recent pulse of greenhouse gases? The world is generally a little warmer since the 1850s; it grew cooler during the decades from 1940 to 1960, to warm still faster in the 1980s. A wonderfully painstaking examination of world climate change over the past century—alert to such recondite details as whether in Victorian times most ships used canvas buckets to fetch up the seawater samples whose temperatures they measured—leads to an unhappy but firm conclusion: the signal of global radiative warming is so far masked by the abundant natural noise. Maybe it will come clear in a decade or so; high hopes are held for new studies on land and sea and from orbit.

Crowley and North conclude with words that hardly ring: "Greenhouse... warming will probably be a very major climate change...[but] there are a sufficient number of caveats to necessitate caution" before we project our global climate models.

The IPCC phalanx closes a little more firmly; they assert certainty about the natural greenhouse and the growth of greenhouse gases and full confidence that greenhouse gases change slowly, so that some of the easier reductions should begin at once. They even venture on prediction, though under the hedging rubric "based on current model results." The future is hard to know. Expect change.

A little reminder from the Environmental Defense Fund that if you're not recycling, you're throwing away a lot more than just your trash.

You and your community can recycle. Please write the Environmental Defense Fund at: EDF-Recycling, 257 Park Avenue South, New York, NY 10010, for a free brochure that will tell you virtually everything you need to know about recycling.

EDF TM Ad Council

An Earthquake an Hour

THE SAN ANDREAS FAULT SYSTEM, CALIFORNIA, edited by Robert E. Wallace. U.S. Geological Survey Professional Paper 1515, 1990. Books and Open-File Reports Section, USGS Federal Center Box 25425, Denver, CO 80225 (paperbound, $20, postpaid).

"An overview of the history, geology, geomorphology, geophysics and seismology of the most well known plate-tectonic boundary in the world," the subtitle runs, setting a high standard for pithy expression. This big paperback is packed with colorful maps, photographs, sections (but no index) that illustrate 10 chapters by USGS investigators. The authors concentrate on the fault system itself, not the urgent public safety issues that have motivated the exhaustive study of this dry-land display of continent-scale motions. Nontechnical but geologically inclined readers will find no barrier here to broad understanding; if they are Californians, they will meet striking local phenomena on most pages.

Only 20 years ago it still seemed "outrageous" to many a land-based geologist to study the San Andreas fault "by using data that is no closer to California than 7,000 km." It is a commonplace now that the complex branching scar that crosses half the length of the Golden State is part of a global system, a zone of slippage between the plate that bears North America and the Pacific Plate. The editor himself, camera in hand, has traveled the length of the fault on land to give readers a wonderful album of a couple of dozen telltale landscapes, the long valleys, aligned lakes and ridges, and offset stream channels that record its fitful motions.

The geologists listen to the fault carefully. A network of a few hundred seismographs linked by telemetry reports even the vibrations during tiny slippages. If you count seismic whispers, a hundred-millionth of the energy of a city-threatening quake, you can log more than an earthquake an hour over the years. The clouds of dots that mark the centers merge into solid swarms at such places as Parkfield or Lake Mono.

The geologists always attend to the past. One colorful drawing shows the wall exposed in a trench strategically cut 20 feet deep about 35 miles northeast of Los Angeles. A dozen layers of peat, silt and pebbly sands show systematic vertical offsets of a foot or so, the result of slippage that has accumulated over the years. Carbon analysis fixes the dates; no mark of the great Fort Tejon shock of 1857 is to be

found, assuring us that here the exposed surface postdates that powerful event. But a dozen earlier quakes are imprinted over the past 1,200 years, irregular clusters of mainly horizontal motion averaging about an inch a year. (The ocean plate moves twice as fast as that; the difference is taken up in many another fault across the West.) The same logic can be applied to grander scales of space and time; geologists have traced an offset between two sections of a single recognizable volcanic flow, shifted north along the fault by 200 miles from the Mojave Desert to the Pinnacles in the Coast Range.

The entire four-dimensional San Andreas system is searched for elastic energy, the ground waves that wreck cities. Naturally, one looks for energy balance. But the waves sent out from known slips are far less powerful than would be predicted from scaling up the rocks in the laboratory. The frictional heat that slippage must generate at depth is not found either. No volcanism is present on the fault. Even the modest peak in heat flow that is predicted right at the fault is missing wherever they have sought it. Lubrication? Is the load overbalanced by pressurized pores? Are there directions of surprising rock weakness? "Most of the story has yet to be learned" at this, the best-known plate boundary in the world.

Our Stars, Ourselves

The Origins of the Mithraic Mysteries: Cosmology and Salvation in the Ancient World, by David Ulansey. Oxford University Press, 1989 (paperbound, $8.95). **The Myth of Replacement: Stars, Gods, and Order in the Universe,** by Thomas D. Worthen. University of Arizona Press, 1991 ($35).

From the first century of this era to the time of Constantine, a secret cult called Mithraism spread through the Roman world, from Scotland to the Black Sea. It was figuratively and literally celebrated underground. An extraordinarily rich iconography in paintings and sculpture records the cult, which left no texts. Its truest believers were the men in the camps, the far-flung troops on whom Rome's power rested. Mithraism never admitted women. Without a Book, without the ties of family, its secret teachings vanished as its triumphant rival, Christianity, claimed emperor and people alike.

For a hundred years, it has been clear that the cult of Mithras celebrated an Iranian god called Mithra. But old Mithra was not at all the young cosmic ruler worshipped by the Roman legionnaires. Mithras is presented in every center of worship as a capped youth stabbing a bull. With him often are sun, moon and constellations: scorpion, snake, cup and dog. Mithra had no such relation to bull-slaying or to any of the creatures.

Over the past two decades, scholars have focused on the implied astronomical connection. In this brief and fascinating paperback (attentive readers of this magazine have already seen the fine summary by Professor Ulansey in the issue of December 1989), the astral mysteries of Mithras are decoded. The capped figure of youthful Perseus (Persian enough!) was always there in the sky above Taurus the Bull. Long before, it had been the very five constellations shown with Mithras that had defined the celestial equator. In that time the last stars visible at dawn when spring arrived were those of Taurus. But Taurus no longer ruled the spring; the celestial axis had shifted. The end of that starry signal was imaged in the slaying of the Bull. Perseus now ruled the spring.

"Let us picture a group of...intellectuals" in the "university city" of Tarsus, known as home to an old Perseus cult. The author asks with a certain audacity: Religious-minded, might they not have greeted with awe the real celestial changes, newly grasped by Hipparchus on Rhodes not far away, and begun to celebrate in secrecy the image of a savior-god who once had shifted the cosmic axis itself?

The second volume, the work of another American classicist, seeks to show within myths in general a sense of change in the celestial order. He attends to the entire domain, not only the Mother Lode of Indo-European myth but even the distant New World.

Worthen opens with a helpful outline of theories of myth, all of which have won some valuable ore of understanding. The old philosophers saw myths as moral parable or as real human history made divine. Newer are the folklorists with their remarkable atomistic motifs, building molecular tales in plenty from a few hundred dramatic elements. Other routes to interpretation include the Jungian appeal to a set of universal ideas of the mind and the learned comparison of Indo-European myths as hints to a few *Ur*-myths of the lost tongues, their true sources.

The author offers his own plausible synthesis at length, generalizing the austere bipolar structures of Claude Lévi-Strauss into rather abstract themes that occur in many guises but need not

be limited to poles of opposition. He lists some nine "bundles of constituents": conflict, sexuality, a Golden Age and a disastrous one, and more. He works out the scheme using the material of his celebrated predecessors in a kind of extensive calibration.

The result is his paradigm for what he calls a myth of replacement. The most novel of its "bundles" is that of right running, a circling motion, always clockwise for well-being, and its ill-omened contrary. (The word "revolution" might do, although it is not his word; nowadays that term means radical replacement even more than it signals real rotary motion.) The fire-making drill, the drill that bores holes, the grist mill, the churn, the wheel and axle, the stirred cauldron—all are basic rotary elements found widely in myth, linked to a change of order. One explicit example is the famous magical Danish mill that once ground gold; broken, now it yields only the salt of the sea.

The etymology of old words often confounds their meanings. An insight here provides a reason why the word "hammer" seems caught up with the word for mill in many Indo-European tongues. How can an ax or a hammer be rotary? Not the use of the ax, but its manufacture was what is rotary. Stone ax blades from the early steppes show laborious rotary drilling of a hole for the haft. The largest instance of order turning to disorder is the slow change in the celestial axis, the precession itself, presumably surmised long before. The ancient stargazers sensed a very slow drift in the season of the year when given stars rose or set in twilight. However reliable they may have been over the centuries, that seasonal drift will bring to an end any coincidence between the season of the sun and the pattern of stars on the horizon. Just such a change would one day depose the Bull as the "regent of springtime." (Worthen offers a somewhat modified account of the origins of Mithras, though still as the precessional Bull slayer.)

Outside the narrow context of Mithras, the diverse decodings are more numerous and less direct. Early in this century a group of scholars claimed a putative Babylonian discovery of precession as the source of all myth. That evident hyperbole did not survive World War I. Now, 20 years after the revival of the role of precession in a wide-ranging if polemic volume, *Hamlet's Mill*, by Giorgio De Santillana and Hertha Von Dechend, new work is at hand. The influence of a long watch over the slow-changing order of heaven seems once more to glow behind the ancient myths.

ESSAY: THE URGE OF AN ANCIENT DREAM by R. W. Lucky

Stuck in a traffic jam, midst a sea of noxious fumes, and surrounded by angry drivers gazing off into nothingness, I pondered the physics of transportation. So much time. So much energy. And yet we have evolved a way of life based on the continual movement of people and objects.

In contrast, the movement of information is so much easier. The celebrated physical laws that speak of the movement of mass are silent about the transportation of that intangible substance we call information. How much energy is required to transmit or process a bit of information? What volume is required for storage? Nature seems to have imposed no lower bounds on these values.

Only a century ago information traveled at the same speed as its human companions. Today it ascends toward incomprehensible gigabit-per-second ranges, where a single bit traveling at the speed of light is but a few centimeters in length. This evolution has transformed the concept of information from bits that are large, clumsy and expensive to bits that are small, agile and cheap. The opportunity this transformation creates for us is to find ways to fulfill the needs of human beings through the virtual world of information rather than through the physical world we have become so dependent on. It is an opportunity that challenges not only scientific innovation but social adaptivity.

The cacophony of honking horns brought me back to the physical reality of automobile travel. We are surely an impatient lot, always on the move, if only for the sake of movement itself. I often think of this incipient anxiety as the remembered urge of an ancient dream—the desire to be somewhere we are not. It is a dream that can be taken as one of the goals for communications technology: using bits as our emissaries, we can redefine the space and time that contain our effective or experienced presence.

For more than a century, the telephone has taken our voices and our ears to faraway places. Recently *Voyager* carried mankind's eye to the distant planets. Soon consumer videophones will give individuals video presence in the homes and offices of friends and associates. Multimedia systems will enable people in scattered locations to share a common visual space and to work cooperatively. Distant users could, for example, jointly edit documents on their computer terminals as if they sat in front of a single display. Networked systems such as these have the potential to break the geographic bonds that compel us to live where we work—undoing an aggregation created by the Industrial Revolution.

Technology has now developed many elements of "telepresence," allowing us to extend our senses to another location. We will be able to gaze at will on a tropical beach, feel the sand on our toes, smell the salty sea breeze and hear the roar of the surf—all from the remoteness of a snowbound cabin in Maine. Other scientists and engineers ask why we should be confined to extending our presence to the world as it is; they experiment with virtual reality prototypes that let us explore places that exist only in imagination.

Much as I would like to eliminate traffic jams, I have no illusions about the difficulties of replacing face-to-face interactions with electronic ones. A government minister, speaking to me about video conferencing, once reached out and embraced me. "I need to smell the person I'm dealing with," he said. Much later, as my embarrassment subsided, I realized that he was speaking of smell as a metaphor for human experience—some essence not conveyed by the electronic medium.

The traditional face-to-face meeting, however, is not necessarily an ideal model for communication. Although electronics cannot reproduce the essence of a human being, conceivably it could facilitate more effective interaction. Perhaps through the mediation and augmentation of computer intelligence, we could actually improve on social dynamics that have remained unchanged since ancient man first sat around the campfire with his fellow hunters.

I looked at my watch and anxiously calculated my chances of getting out of the gridlock in time for my morning meeting. Another ancient dream drifted through my unfocused mind—the desire to be in some time we are not. Regretfully, I rule out physical time travel, but virtual time travel is a new and suddenly important role for those plentiful bits of information. The venerable telephone network does not really work anymore, simply because no one is at home when the phone rings. The answering machine is a starting point, but we need to develop communications surrogates that can handle our communications when we are unavailable, which is getting to be most of the time. Maybe they can do a better job of it anyway.

I thought of other ancient dreams that could be realized. Magazines, movies and television continually remind us that we harbor the desire to be someone we are not. This dream is probably most evident today in broadcast television, where our vicarious experiences are played out in soap operas and on football fields. What technology has to offer is increased realism in these fantasies. Soon there will be high-definition television, and then wide-screen 3-D television. Multimedia systems based on interactive videodisc technology will mean that we can explore subject matter as if we were experiencing it. Being placed in someone else's shoes offers dramatic potential for entertainment and education.

In the midst of hundreds of immobile drivers, I was alone in the compartment of my car. A feeling of isolation pressed on me. We have yet another ancient dream—the desire to be something we are not. Can we join electronically in creative ways with our fellows to achieve a collective wisdom that transcends the individual? Today's computer bulletin boards show the way. I yearn for an electronic global town commons, for a virtual coffeeshop where I can meet the wise people of the world. I yearn for a new democracy shaped by opinions argued by virtual, worldwide communities.

I want so much from those nimble bits. But there I was, futilely enmeshed in the crowded meeting place of those mechanical conveyance units we call cars. There must be a better way.

R. W. LUCKY is executive director of research at AT&T Bell Laboratories.

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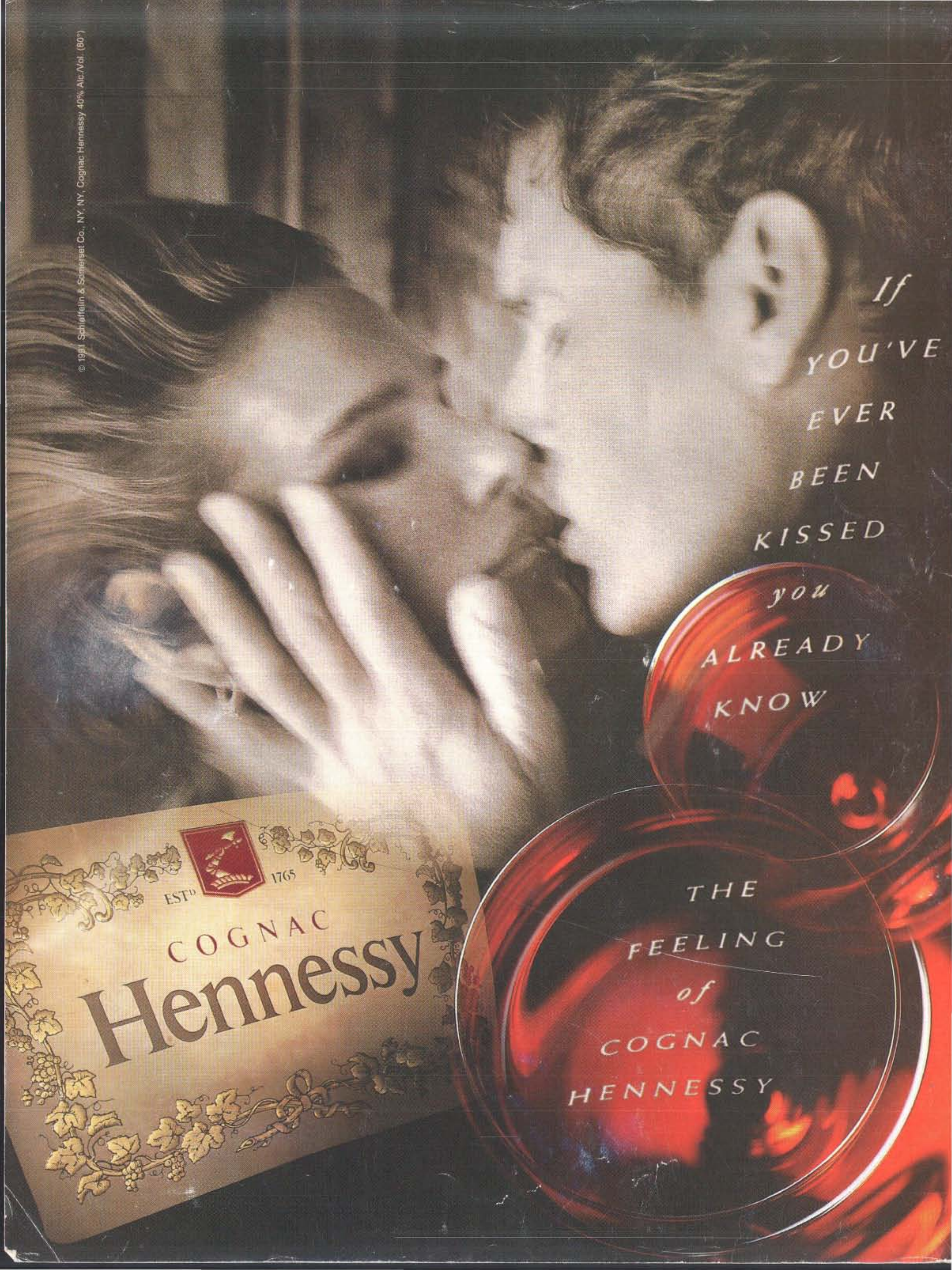
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